SUMMARY

A concept for an ecosystems function model (EFM) for the lowland alluvial river systems of California's Central Valley is described. The model would assist the conceptual design of potential measures for flood damage reduction and environmental restoration, indicate their expected impacts, and enable a retrospective evaluation of their effectiveness. The array of potential measures is broad and includes:

- creating or modifying flood storage capacity and/or reservoir release schedules or otherwise affecting flow regimes;

- removing, setting back, or raising levees; constructing backup levees; improving bypass systems; managing floodway vegetation and sediment; modifying floodways to allow natural river processes; or otherwise modifying floodway conveyance capacity;

- protecting streambanks, reinforcing and repairing levees or otherwise increasing flood-control-system reliability; and

- modifying, discouraging, or redirecting incompatible existing or future floodplain development or otherwise improving floodplain management.

The model would combine streamflow information from hydrologic and hydraulic models now under development by the Corps with information from other sources to characterize likely effects of measures on important ecosystem attributes. It would provide quantitative comparisons of the amount, spatial distribution, and dynamic character of aquatic, wetland, and riparian habitats under existing conditions, future-without-action conditions, and conditions following implementation of the various measures that warrant detailed consideration.

Specific indicators of key ecosystem attributes and the physical attributes influencing them in the lowland alluvial river ecosystems are identified in this report. Ecosystem modeling concepts developed in the CALFED process provided the point of departure for this identification. Key ecosystem attributes are those that address species of concern to resource managers in the Central Valley, appear sensitive to changes that would result from proposed measures, can be quantified from available or readily obtainable data, and encompass both ecosystem state and ecosystem process (dynamics). Selected indicators of these attributes, presented in map or statistical form, would address the following ecosystem attributes:

<u>Aquatic Habitats</u>

- extent and diversity of permanent and seasonal aquatic habitats;
- inundation and velocity regimes for channels and overbank areas;
- connectivity of floodplain aquatic features;
- streambank habitat value;
- input of instream cover; and
- channel substrate, morphology, and stability.

Terrestrial Habitats

- topographic, soil, and groundwater conditions suitable for riparian/wetland vegetation communities;
- floodplain inundation regimes suitable for establishment and survival of riparian/wetland vegetation communities;
- dynamics of channel migration and habitat renewal;
- dynamics of vegetative succession; and
- wildlife habitat suitability related to the distribution of vegetation communities.

A step-by-step process for developing the model is presented in detail (Appendix D). Specific quantified relationships between physical variables and ecosystem responses would be established in the first phase of model development. These relationships would be derived from existing studies and models for the basins (e.g., channel migration and plant growth and succession studies and models) and inferences from similar work in other regions. Ecologists experienced in aquatic and riparian habitat studies along streams within the Central Valley would direct these efforts. The primary physical variables would be the seasonal and long-term streamflow and sediment transport regimes that reflect both typical conditions and the episodic cycles of flood and drought.

In this modeling effort, biochemical processes would be represented by their physical manifestations. The connectivity of floodplain features (e.g., sloughs, oxbows, toe drains) affects the flow of nutrients from backwater habitats to the flowing-water habitats. Modeling the physical processes would therefore illustrate the importance of the nutrient flows represented by these floodplain features.

The analysis of physical conditions will indicate the potential extent and dynamic nature of habitat that would most likely be present in the absence of human disturbance. These conditions can be beneficially or detrimentally affected by land use and floodplain management practices. As a final step in the analysis, potential habitat characteristics would be modified to reflect the superimposed effects of existing or proposed land use. This step will result in maps and statistical summaries of both the predicted and "natural" habitat conditions.

The model would be structured for simulation of individual river reaches, entire rivers, or the entire Sacramento and San Joaquin River basins, providing flexibility in addressing key issues, schedules, and cost constraints of the Comprehensive Study. It would also be structured to accommodate the future development of new predictive techniques or additional data relating physical conditions to biological processes that characterize Central Valley ecosystems, thereby serving as a valuable tool for ongoing adaptive management of the flood control systems.

TABLE OF CONTENTS

TABLES

FIGURES

APPENDICES

1.0 BACKGROUND

1.1 OBJECTIVES OF THE COMPREHENSIVE STUDY

The Sacramento and San Joaquin River Basins Comprehensive Study (Comprehensive Study) was initiated by the U.S. Army Corps of Engineers (Corps), The Reclamation Board of the State of California (The Reclamation Board), and the California Department of Water Resources (DWR) in cooperation with several other state and federal agencies. The purpose of the study is to develop a systemwide, comprehensive flood-management plan for the Central Valley to reduce flood damage and integrate ecosystem restoration. Measures will be proposed and evaluated that address both of these general objectives. Specific objectives of the Comprehensive Study are described in Appendix A. Objectives explicitly related to environmental functions are to:

- develop tools to analyze the hydrologic, hydraulic, geomorphic, and biologic processes of the flood management system;
- increase and improve riparian, floodplain, floodbasin, and riverine habitats throughout the Sacramento River flood management system using an ecosystem approach;
- promote the stability of native species populations and recovery of threatened and endangered species in the flood management system;
- promote natural, dynamic, hydrologic, and geomorphic processes in the flood management system;
- preserve agricultural productivity while promoting the ecological value of agricultural land;
- incorporate environmental restoration features into the design of federal, state, and local elements of the flood management system;
- minimize flood management system operation and maintenance requirements and associated costs;
- allow for adaptive management of the system in response to changes over time; and
- compensate for unavoidable adverse socioeconomic, land use, and environmental impacts associated with flood management actions.

The Comprehensive Study was initiated in October 1997 and will conclude with a final report in 2002. The study is being conducted in two phases. During the first phase, the Corps is conducting a post flood assessment of four recent floods, developing hydrologic and hydraulic (H&H) models of the two river systems, and preparing an interim report. The interim report will describe baseline conditions; the status of the hydrologic and hydraulic models; and the status of the ecosystem functions model (EFM), which is outlined conceptually herein, and will summarize the results of the post flood assessment, identify flood damage reduction and interrelated ecosystem restoration measures, and describe the plan of action for the second phase of the study.

During the second phase of the Comprehensive Study, measures and combinations of measures will be evaluated to determine both flood damage reduction and environmental benefits. Potential adverse impacts of selected alternative measures will be evaluated. This phase of the study is expected to conclude with a feasibility-level report and a programmatic environmental impact statement/environmental impact report (EIS/EIR). These reports will document the calibration of the EFM and present the results of simulations used for design and environmental impact analysis.

1.2 MANAGEMENT MEASURES CONSIDERED IN THE COMPREHENSIVE STUDY

A preliminary list of possible measures to reduce flood damage and restore environmental values has been developed for the Comprehensive Study. Under the direction of the Comprehensive Study Team (Study Team), Jones & Stokes Associates (JSA) compiled potential measures from many sources and from them developed a list of measure types. Table 1 indicates the types of measures identified. In general terms, the measures involve:

- creating or modifying storage capacity and/or reservoir release schedules or otherwise affecting flow regimes;

- removing, setting back, or raising levees; constructing backup levees; improving bypass systems; managing floodway vegetation and sediment; facilitating natural river channel migration; or otherwise modifying floodway conveyance capacity;

- protecting streambanks and repairing levees, or otherwise increasing system reliability; and

- modifying, discouraging, or redirecting incompatible existing or future floodplain development or otherwise revising floodplain management.

These types of measures may be implemented at varying scales in any number of places in the Sacramento and San Joaquin River basins. Characteristics of these measures that may vary from place to place include changes in the amount and seasonal pattern of reservoir releases; the length or amount of levee setback; the extent, depth, and duration of controlled overflow-basin inundation; the locations and amounts of channel capacity modification; and the location and hydraulic roughness of new vegetation.

2.0 PURPOSE OF THE ECOSYSTEM FUNCTIONS MODEL

An EFM has been identified as important to accomplishing the purposes of the Comprehensive Study. Such a model should assist the conceptual design of potential measures for flood damage reduction and environmental restoration, indicate expected impacts of those measures, and enable a retrospective evaluation of their effectiveness. The EFM should combine streamflow information from the H&H models with information from other sources to characterize likely effects of measures on important ecosystem attributes.

The EFM is intended to be an analysis tool to support planning, implementation, and monitoring of flood damage reduction and environmental restoration measures along rivers and streams and within floodbasins of California's Central Valley. Models explicitly identify the parameters and relationships being used for analysis, rapidly analyze large amounts of data, provide the capability to vary and test assumptions with repetitive data analyses, and identify sensitive variables. The EFM will integrate known geomorphic and ecosystem principles and available information regarding important attributes of alluvial river ecosystems into an analysis tool that can be used by natural resources planners and engineers. It will provide quantitative comparisons of the overall amount, spatial distribution, and dynamic properties of major aquatic and riparian habitat types under existing conditions, future-without-action conditions, and conditions following implementation of various measures and combinations of measures for flood damage reduction and ecosystem restoration. This information will be important for designing measures and evaluating their environmental effects. To achieve this objective, the EFM will:

- be applicable to a range of geographic scales, from river reaches a few miles long to the entire river system in the Central Valley;
- allow for focus on particular ecosystem components or comprehensive analysis of the entire river-floodplain ecosystem, depending on key issues, available information, and design detail of measures under consideration;
- simulate cause-effect relationships of most apparent importance and for which data are available or can be feasibly obtained in the near term;
- be based on scientifically sound principles;
- afford ease of updating the model and incorporating new data or revised relationships among ecosystem attributes;
- guide planning by identifying habitat criteria and areas on the land that match those criteria; and
- be accessible and easy to use by a range of potential users.

The objective of this report is to describe the conceptual model, its capabilities and limitations, and the steps required to translate the conceptual model into a working EFM, including the information that will be drawn from the Corps' H&H models and other specific data.

To evaluate the effects of some management measures, it may be necessary to simulate only the reach of river modified by the measures (as described in "Spatial Scale of Analyses" below). However, the EFM will be designed to simulate all of the waterways included in the Corps' hydraulic models simultaneously to evaluate effects related to habitat continuity and provide accounting of the total acreage and distribution of the simulated habitat types in the Sacramento and San Joaquin Valleys.

3.0 RELATIONSHIP TO CALFED ECOSYSTEM FUNCTION MODEL CONCEPT DEVELOPMENT

This EFM was formulated by first considering existing ecosystem-modeling concepts of potential relevance to the Comprehensive Study (Levy et al. 1996, Young et al. 1997), especially concepts formulated by scientists associated with the CALFED process in California. Several groups within CALFED have addressed ecosystem-functions modeling over the past few years and continue to do so. Recent formulations by these groups regarding model concepts and important attributes of lowland alluvial river ecosystems (Appendix B) provided a point of departure for EFM development and guided overall development of the model. This EFM proposal extends those concepts to applications focused on the needs of the Comprehensive Study, as previously described. The model is not intended, however, to link aspects of management of California's water supply, using lowland rivers for conveyance, to effects on downstream estuaries of the San Francisco Bay-Delta region—a major concern of CALFED.

An ongoing need will be to continue to coordinate development and implementation of this model with further model-concept development by the CALFED investigators. To meet this need, links have been forged between this model-development process and the new Strategic Plan process of CALFED. The Study Team is also coordinating with various CALFED committees and working groups, and a representative of CALFED participates in the Comprehensive Study as a member of its Executive Committee.

4.0 DEFINITION OF TERMS

An ecosystem is a biological community together with the physical and chemical conditions and resources of its location (Warren 1971). It includes natural physical, chemical, and biological processes as well as people and their activities within the same geographic area.

4.1 ECOSYSTEM FUNCTIONS MODEL

An ecosystem functions model comprises variables representing key attributes or characteristics of the system and the relationships among those variables. It provides a framework to help prioritize, organize, and analyze information about the natural ecosystem, detect problems, and identify a range of appropriate solutions (Lestelle et al. 1996). An EFM includes a conceptual model and a mathematical model that quantitatively implements the conceptual model.

4.2 ECOSYSTEM ATTRIBUTES

CALFED scientists defined "ecosystem attributes" at a conceptual level as "those fundamental natural ecological characteristics that together define and distinguish the system, its status, and its interrelationships" (Young et al. 1997). They made a distinction between "structural attributes" and "functional attributes".

Structural attributes refer to the physical and biological components of an ecosystem and their spatial relationships to one another (Levy et al. 1996). For example, physical structural attributes include the presence or diversity of various types of hydrogeomorphic features in floodplain ecosystems, including mainstem channel morphology and bank vegetation, side channels, flood channels, oxbows (cut off former channels), distributary and drainage sloughs, overflow basins, the mosaic of floodplain and upland elevations and soil types, and the underlying water table. Biological structural attributes include the populations of species within an ecosystem, the diversity of species, and spatial distributions of species (e.g., habitat types), including transitions in vegetation type along moisture and inundation-frequency gradients. In a mathematical EFM, structural attributes are state variables that have a magnitude and location, which can be used to describe the condition of the system at a given point in time.

Functional attributes refer to the physical, chemical, and biological processes that contribute to the development and maintenance of the ecosystem (Levy et al. 1996). These processes are the dynamic interactions among the structural components of the ecosystem and are chiefly characterized by rates of change. Key physical processes in alluvial river ecosystems include streamflow (e.g., temporal patterns of inundation and shear stress), water-temperature fluctuation, erosion and deposition of substrate, and water-table depth fluctuation. Chemical processes include nutrient or contaminant input and movement. Biological processes include substrate colonization, growth, succession, and senescence of riparian plant communities; biomass production; allochthonous input from riparian communities to the aquatic system; predation (including disease); and competition. In a mathematical EFM, functional attributes are equations and logical operators that describe interactions between variables and the direction and rates of change in the ecosystem.

4.3 ECOSYSTEM INDICATORS

Ecosystem indicators are measurable attributes that provide a quantitative indication of ecological integrity. Indicators can reveal the direction and magnitude of change from existing conditions. They can also show whether the ecosystem is moving toward or away from an intended healthy condition ("normative condition") and therefore whether management measures have been successful (Young et al. 1997). Indicators must collectively represent all of the important ecological attributes of the system (Levy et al. 1996).

Indicators are usually, but need not be, attributes that are directly simulated in an EFM. For example, the population of chinook salmon could be measurable and may be considered an indicator of the health or desired condition of the ecosystem; however, a model might not simulate the population directly because of the large number of factors that affect populations. A model would more appropriately simulate only those attributes affecting salmon populations that are expected to be affected by the management measures included in the Comprehensive Study.

Values of ecosystem indicators, such as habitat acreages or rates of habitat-type change, may be estimated by both specific spatial-temporal simulations or by more general statistical means. Predicting the actual location and sequence of change in a riverine system (e.g., river channel migration or plant succession) is highly uncertain because of the many site-specific variables involved; however, simulating long-term average rates of change along a river/floodplain reach will provide a useful indicator for assessing changes to dynamic ecosystem attributes.

5.0 CONCEPTUAL ECOSYSTEM FUNCTIONS MODEL

Any model is necessarily a simplified representation of the real system. Simulation of the entire ecosystem in detail is not feasible because of the vast number of ecosystem attributes, the high degree of spatial and temporal variability in those attributes, and the lack of knowledge about many of them. The EFM described here will focus on <u>key</u> attributes and relationships, potentially affected by the measures under consideration, as perceived by Jones & Stokes Associates' ecologists experienced within the basin. These attributes and relationships are described below, following a discussion of the model framework.

5.1 MODEL FRAMEWORK

This section describes the structure and scope of the proposed EFM and its resulting capabilities. Limitations of the model are noted here as well, but are described in more detail in Appendix C, "Model Limitations".

5.1.1 PHASING MODEL DEVELOPMENT

The EFM described in this report will be applicable to any given measure or combination of measures at a particular location. If desired, habitat conditions throughout the Sacramento and San Joaquin Valleys may be simulated simultaneously so that offsite effects of the measure may be analyzed and the overall effects may be evaluated in a regional context. For computational convenience, specific steps of the modeling procedure may be completed individually for geographical subareas and combined to obtain results for the entire study area.

Within the present scope of the Comprehensive Study, the EFM will be developed in several stages concurrent with completion of the H&H and sediment transport models. The first step will be to create a model that includes the full suite of attributes and functional relationships described below but is applicable to only one river reach at a time. This step may include placeholder functions for stage-discharge relationships (e.g., normal-depth calculations based on Manning's law using current hydrology), floodbasin inundation, and sediment transport. This step can be completed concurrently with development and calibration of the inchannel hydraulics models (expected to be completed by spring 1999). Incorporation of correct stage-discharge relationships, flooding outside the levees, and sediment transport functions (i.e., HEC-6), plus expansion to simulate all reaches included in the H&H models simultaneously, can be completed within several months following completion of the H&H and sediment transport models (or by approximately summer 2000).

The model will be expandable to include additional biological attribute categories and additional quantitative information regarding physical and biological functional relationships as that information becomes available. Potential model enhancements that are not included in the present scope of the Comprehensive Study effort are described later under "Future Model Refinement".

5.1.2 GEOGRAPHIC FOCUS OF EFM

5.1.2.1 Geographic Extent. In considering issues associated with the flow of water through the Sacramento-San Joaquin Bay-Delta system, CALFED scientists recognized the great complexity of ecosystems within the 41,000 square-mile watershed. The entire system includes mountainous uplands (with intermontane alluvial valleys), the alluvial river basins of the Central Valley floor, the Delta of the two major rivers, Suisun and San Francisco Bays, and nearshore marine areas (Young et al. 1997). Included are wide ranges in human populations and alteration of natural systems. These scientists therefore developed a typology of ecosystem classification using different geographic scales. It begins with general landscape types that are divided into multiple ecosystems, which are further divided into numerous habitats. Consistent with the purpose of the Comprehensive Study, the EFM described here addresses the alluvial river floodplain landscape (or lowland river floodplain system), which is one of five landscape types identified by CALFED.

Lands downstream of the network of major reservoirs along the periphery of the basin floor (typically below an elevation of about 300 feet, where most inflowing streams become alluvial in nature) constitute the geographic range of applicability of this EFM (Figure 1). The focus on lowland alluvial river ecosystems stems from the focus of the Comprehensive Study on flood management on the Valley floor, and especially along mainstem and major tributaries of the Sacramento and San Joaquin Rivers. Within the Delta, however, only lands and waters between the existing federal levee system along the mainstems of the Sacramento and San Joaquin Rivers and major distributaries would be addressed by this EFM. The larger Delta estuarine and tidally influenced ecosystem, including the complex network of local flood control levees and island agriculture, is being addressed through the CALFED process.

5.1.2.2 General Habitat Types Encompassed. Flood management on the basin floor involves flood storage reservoirs, mainstem and tributary river channels, floodplains, overflow basins, leveed floodways, and flood bypasses. Accordingly, the EFM will address habitat types (described below) that are directly linked to those elements.

- Lotic aquatic (or flowing water) habitats include the main channel and side channels.

- Lentic aquatic habitats (standing or slowly flowing water) include sloughs, oxbow lakes, marshes, and levee toe drains that are disconnected from the main channel at low flow but are inundated during higher flow events.

- Floodplain habitats are alluvial areas near a river channel that have been constructed through sediment deposition and erosion and are periodically inundated during higher flows. In addition to aquatic habitats, they include primarily woody riparian habitats or cleared agricultural areas.

- Floodbasin habitats are offchannel areas that are inundated during high flow events but where water may remain standing for long periods after river stage recedes; these are also lentic habitats, or seasonal wetlands, that historically supported tule marsh vegetation. Current flood bypasses comprise portions of historical floodbasins, and flow to flood bypasses is now regulated by weirs. Flood bypasses are commonly farmed, but also support a variety of smaller lotic and lentic aquatic, riparian, and marsh habitats.

5.1.2.3 General Substrate Types Encompassed. For purposes of the EFM, river-floodplain systems in the Sacramento and San Joaquin River basins can also be grouped into categories based on substrate characteristics. The categories would be based on dominant sediment size—either coarse or fine grain. River reaches are classified as coarse grain if the dominant riverbed sediment texture is gravel or cobble, and as fine grain if the dominant bed texture is sand or silt.

Dominant sediment size is an important ecosystem attribute from both geomorphic and biological perspectives. Channel migration (including potential channel migration now constrained by riprap) is influenced by the size and cohesiveness of substrate materials. Biological communities and processes also differ substantially according to the dominant sediment type. For example, spawning by chinook salmon, steelhead, and other species is restricted to reaches having a coarse-grain channelbed.

5.1.3 FOCUS ON PHYSICAL PROCESSES

Alluvial rivers are systems characterized by high kinetic energy and mobile substrates, and episodic morphologic change is the primary characteristic of this landscape. Habitats are created, pass through temporary, relatively stable successional phases, and are subsequently altered or destroyed. Accordingly, an EFM for lowland alluvial river floodplain ecosystems will tend to focus on physical processes.

Biochemical processes, while not dominant as they are in the Delta estuarine environment, also play an important role in alluvial river ecosystems. The connectivity of floodplain features (e.g., sloughs, oxbows, drains) affects the flow of nutrients from these lentic aquatic habitats to the mainstem lotic aquatic habitats, thus affecting fish and other aquatic species within the system. A modeling of the physical processes affecting these features, however, is sufficient to assess their potential presence, persistence, and degree of hydrologic connectivity to the mainstem rivers. Independent modeling of nutrient flows is therefore not essential and, because of scarcity of data, would be difficult to formulate.

5.1.4 SPATIAL SCALE OF ANALYSES

Floodflows in the Sacramento and San Joaquin Rivers are affected by timing and amounts of runoff from all parts of their respective watersheds as well as by the capacities and operation of flood control structures throughout the watersheds. Effective flood management therefore requires an ability to consider the entire watershed at one time, which is one goal of the H&H modeling program.

Many important ecosystem attributes operate at a relatively local scale and are largely independent of environmental conditions tens to hundreds of miles away. For example, most of the direct ecosystem effects of constructing a setback levee and widening the floodplain occur along the modified reach. Simulation of the entire river system is not needed to evaluate these direct effects. However, migratory species such as anadromous fish, waterfowl, and neotropical songbirds are affected by the continuity of habitat conditions over long distances. Additionally, it is useful to be able to map and tabulate totals and statistics for habitat throughout the Central Valley as a means by which to achieve the greatest amount of overall habitat value within the context of flood management. Accordingly, the EFM will be capable of simulating at one time all of the waterways included in the H&H modeling program.

For the basic unit of analysis, the EFM will evaluate ecosystem conditions along fairly long "management" reaches of major rivers and bypasses. Management reaches are those areas of a river-floodplain system along which flow, substrate, and channel and floodplain geomorphology are relatively constant. Management reaches will generally be tens of miles long and will include several river segments used in the H&H modeling. This scale of analysis is adequate to evaluate the local effects of many management measures (e.g., a reach of setback levee, a new floodbasin, or reoperation of a single reservoir).

The smallest spatial scale of analysis in the model will be on the order of tens to hundreds of feet horizontally and 1 foot vertically. Different variables within the model will have different scales of spatial resolution. Digital terrain models are expected to have the finest scale of resolution. Hydrographic and topographic data in the mainstem river channels and within 300 feet of the channel levees are based on a terrain-model surface with a horizontal accuracy of 3 feet and a vertical accuracy of approximately 1 foot. It is envisioned that the overbank areas will be based on data from either Laser-based surveys (i.e., LIDAR) or from existing U.S. Geological Survey (USGS) 7.5-minute quadrangle sheet data. The LIDAR data would have point elevations every 6.56 to 39.36 feet (2 to 12 meters), with a vertical accuracy of 0.5 foot (15 centimeters), and the USGS data would be based on point elevations every 98.4 feet (30 meters), with a vertical accuracy of 5 to 10 feet (1.52 to 3.048 meters). Other important variables, such as soil type and land use, are mapped to within tens of feet. The digital topographic data do not show small topographic features that may be important to sustaining wetlands. Although the EFM cannot simulate all of these features, they can still be accommodated in the detailed design of measures.

The topographic data will be used in the EFM to create floodplain maps for various flow and stage levels in the rivers. River stage will be calculated only at cross sections located at 1, 000- to 5,000-feet intervals, and the water surface profiles and floodplain maps along the river segments between those locations will be based on linear interpolation of stage.

Although the accuracy of simulated effects at a given location along the river might be only fair, the overall trend in habitat conditions in response to management measures along a management reach is more likely to be simulated correctly. This effect of "compensating errors" commonly results from simulating an entire population (the fluvial ecosystem) from discrete sample points (the cross sections). Each cross section may not be highly representative of the entire management reach, but the combination of several cross sections will most likely be representative.

Some ecosystem attributes vary only at much larger scales within the system. Ecosystem processes that are substantially affected by the continuity of conditions over long distances within the watersheds include water temperature, nutrient transport, some aspects of sediment transport, fish migration, avian and large mammal movement, and seed dispersal. Diversity and continuity of plant communities are also attributes that must be considered over a broad area. Major changes in these regional attributes generally would not result from the management measures, but where issues arise, systemwide model elements would need to be developed in subsequent modeling phases. In the initial EFM model, however, the conditions of these attributes will be summarized for each management reach being assessed.

5.1.5 TEMPORAL SCALE OF ANALYSES

The dynamics of fluctuations in riverflow will be addressed in the model by analyzing daily streamflow data for several decades to determine flow thresholds that meet selected seasonal duration and annual frequency criteria relevant to particular biological processes.

Time scales of interest for ecological processes range from continuous variability (e.g., air and water temperatures) to diurnal (e.g., light), seasonal (e.g., flow), decadal (plant community succession), and millennia (river channel migration). The state of the ecosystem at any point in time reflects the combined effects of processes at all time scales. In some reaches, for example, the dynamics of channel migration control the rate at which mature vegetation is eliminated and new point bar deposits suitable for the establishment of early succession vegetation types are created. Currently, it is impractical (and unnecessary) to simulate the state of all needed ecosystem attributes at specific locations (e.g., a grid of model nodes) because they change through time at all of these temporal scales. The impracticality stems from only partial understanding of physical processes at work as well as absence of spatially detailed data necessary to support spatial-temporal model calculations.

For example, the ability to predict locations and amounts of change in channel location during flood events is primitive, although graphical simulations of possible future migration are being developed for a portion of the alluvial reach of the Sacramento River (Larsen pers. comm.). Such specific spatial-temporal simulations of migration, although valuable for some purposes, such as estimating typical effects of bank protection on channel migration, do not need to be developed for the entire river systems for predicting ecosystem behavior over the long term. Predictions of average rates but not the exact sequences of channel migration and subsequent plant succession are needed.

5.1.5.1 Use of Average Annual Rates for Highly Variable Ecosystem Dynamics. Instead of simulating the state of all needed ecosystem attributes at specific locations through each point in time, the EFM will address ecosystem dynamics and trends (e.g., sediment transport and plant community succession) as average annual rates along a management reach. For episodic events, such as channel migration, the average annual rate should be interpreted only as the estimated long-term average rate of change in channel location along the management reach.

It is recognized that many ecosystem changes do not occur gradually or uniformly through time. Some ecosystem processes, such as sediment transport and channel migration, are highly episodic because they are nonlinear functions of flow and because high flows are not regularly distributed in time. The methods used to evaluate those processes will reflect the full dynamics of the flow regime but the results will be reported as an average annual rate for an entire reach to avoid implying an unrealistically high level of spatial accuracy. In many cases, average annual rates over a broad area can be simulated relatively reliably, whereas the chronology of change at a single location cannot.

In the EFM, channel migration will be characterized statistically as an average annual "turnover rate" of riparian habitat for a given river reach (tens of miles long). The turnover rate can be estimated by dividing the total area subject to channel migration along a river reach (in acres) by the average annual channel migration rate along that reach (in acres per year). Historical channel migration data, as well as the results of site-specific applications of spatial-temporal channel migration models (e.g., Larsen's), will be used to provide the average annual channel migration rates to simulate effects of different management measures.

Channel migration models capable of correctly simulating the specific locations and timing of channel migration in a river system may eventually be developed. The EFM could be enhanced by incorporating those models when they become available (see "Future Model Refinement" below), although that is beyond the scope of the Comprehensive Study.

5.1.5.2 Variable Temporal Scales for Different Life Stages. The model will address short-term dynamics related to reproduction and regeneration of vegetation communities and key species by evaluating habitat conditions for different life stages separately. For example, the maximum depth to groundwater that can be tolerated by seedlings of some phreatophytes (water-loving plants) is much less than the depth that can be tolerated by mature individuals of the same species. Similarly, inundation of vegetated floodplains is of greater importance to juvenile salmonids (for shallow cover and food supply) than to adults.

5.1.6 SIMULATING BIOLOGICAL ENTITIES

The great diversity of species in the alluvial river ecosystems of the Sacramento and San Joaquin River basins precludes simulation of all species individually. Likewise, simulation of the innumerable variations in plant community composition at different locations would be an insurmountable task. The EFM will simplify the biological complexity of the ecosystem to a manageable level by focusing on requirements of representative aquatic organisms and major terrestrial plant communities. The aquatic species on which the EFM will focus are those that are present throughout most of the river basin system and are dependent on specific physical attributes that affect a large number of organisms. Describing their habitat requirements and physical attributes that affect such habitat can serve as a surrogate for habitat availability for many species. Likewise, simulating only major terrestrial plant communities is a reasonable approach if individual species and diversity of microhabitats within the community are not disproportionately affected by management measures.

5.2 SELECTION AND RELATIONSHIPS OF ATTRIBUTES

5.2.1 INTRODUCTION

The following describes the actual ecosystem attributes selected for simulation in the model, how they are related to one another, and which will be used in model output as indicators. For the initial version of the model, attributes have been selected and defined so that they:

- clearly address species and communities of particular interest to resource managers (e.g., chinook salmon, species listed and proposed for listing under the Endangered Species Act [ESA], wetlands, riparian vegetation);

- are sensitive to and representative of the effects of potential measures for flood damage reduction and environmental restoration so that the measures can be meaningfully compared;

- can be quantified using available or readily obtainable data; and

- encompass ecosystem dynamics (e.g., geomorphic processes and vegetative succession) as well as ecosystem state (i.e., habitat acreages).

As a starting point, the comprehensive list of ecosystem attributes developed by CALFED scientists for the lowland alluvial river floodplain ecosystem (Appendix B) was reviewed for its applicability to the management measures being considered in the Comprehensive Study. The five general attribute categories identified by CALFED include:

- general hydrologic attributes,
- general geomorphic attributes,
- habitat attributes,
- native biological community attributes, and
- community energetics/nutrient cycling attributes.

The initial EFM will address the first three categories completely. From the fourth category, vegetative community succession will be simulated and the user may choose to add biological categories to represent non-native species. The fifth category of attributes comprises various aggregated or synergistic ecosystem characteristics such as primary productivity, nutrient and energy transfers among trophic levels, species diversity, and geographic variations in communities. The model will not simulate these attributes directly because the functional relationships involved are not well understood and because they are accommodated by the focus on physical processes, as discussed previously.

Ecosystem attributes that will be included in the EFM can be grouped into two broad categories: physical attributes and biological attributes. These are defined below.

- Physical attributes include topography, streamflow, and geomorphic characteristics, which collectively affect the timing, duration, and frequency of inundation; water depth; flow velocity; and substrate processes, including erosion, deposition, and channel migration. Physical attributes selected are those that drive key biological attributes or indicators.

- Biological attributes are selected habitat characteristics and processes, based on consideration of habitat requirements of representative aquatic species and major terrestrial plant communities.

The specific physical and biological attributes to be included in the model, and the rationale for selecting them, are described in the following sections. The general relationships between selected physical and biological attributes are discussed. During a pilot application period, the specific actual mathematical functions to represent these relationships will be formulated based on detailed review of the scientific literature and on field observations. These relationships may be either quantitative (where available data support their development) or qualitative (where biologists agree on general relationships and associations but have no empirical experimental data with which to develop quantitative relationships). If existing information is insufficient to identify appropriate relationships, the Study Team will collaborate with affected stakeholders to determine an approach for developing appropriate relationships.

5.2.2 PHYSICAL ATTRIBUTES

5.2.2.1 Topography. Topography is the shape and elevation of the ground surface, including parts of the riverbed that are normally under water. Topography is important in lowland alluvial river ecosystems principally because it interacts with the flow regime to create complex spatial distributions and gradients in inundation and depth to the water table. Topography also controls connectivity between the main river channel and various floodplain aquatic habitats, such as toe drains and borrow pits, side channels, sloughs, oxbow lakes, ponds, and floodbasin wetlands. Topography intertwines with hydrology to form major physical attributes of the river systems.

5.2.2.2 Hydrology. Flow regime is a key attribute that directly affects the distribution and abundance of aquatic and terrestrial species in lowland alluvial river ecosystems. Key attributes related to flow regime and topography and their general relationships are shown in Figure 2. Flow varies continuously with time and space along the rivers and floodplains, but specific characteristics of the overall flow regime can be defined as separate attributes of particular relevance to ecological processes. Some relevant flow-regime attributes describe high-flow characteristics important to seasonal inundation, which recharges soil moisture and promotes seedling germination. Other flow-regime attributes describe low-flow conditions important to water-table depth and plant performance during the growing season. For example, a flow-regime attribute important to establishment of cottonwood seedlings is the rate of river-stage decline from April through August.

The depth to the water table strongly influences the distribution of riparian vegetation because many riparian tree and shrub species are phreatophytes that require the presence of a relatively shallow water table. The water table near major river channels in the Central Valley is usually in hydraulic connection with the river and slopes upward or downward away from it fairly gradually, depending on regional groundwater conditions. The water table locally rises and falls with changes in river stage. With increasing distance from the channel, recharge, well pumping, and leakage to underlying aquifers play an increasingly strong role, and the water table may gradually become higher or lower than the river's water surface.

Spatial variations in flow, topography, and depth to the water table strongly affect the complexity and diversity of habitats. The EFM will include a mapping component that evaluates hydrologic attributes in considerable spatial detail. This detail is made possible by the availability of high-resolution digital topographic data, records of daily historical flows at numerous gages throughout the river basins, and hydraulics formulas and models that can be used to simulate inundation regimes and water-surface elevations during the growing season between gage locations.

5.2.2.3 Geomorphology. Geomorphic processes and effects of particular ecological importance are a) sediment gradation and transport, b) rates of channel migration, and c) the shapes and locations of channel and floodplain features.

5.2.2.3.1 Sediment Transport. Sediment transport processes affect the grain size distribution of sediment in a given river reach and the tendency toward aggradation or degradation of the channel. Streambed sediment texture affects suitability for fish spawning and for establishment of riparian vegetation. Aggradation and degradation affect flood conveyance capacity and channel migration. Suspended sediment (sand, silt, and clay) contributes to soil accretion on floodplains and floodbasins during flood events and results in variations in water-holding capacity of floodplain soils.

Sediment transport will be simulated by the Corps using HEC-6, a sediment transport model that can be coupled to the hydraulics models. HEC-6 applies incipient-motion equations and mass continuity to calculate the one-dimensional (downstream) rate of sediment transport and the tendency toward net aggradation or degradation along each reach. Input data will include sediment texture data available for many locations along the major Central Valley rivers. HEC-6 can also provide some indication of changes in riverbed sediment texture that might result from changes in flow regime. HEC-6 does not directly simulate small-scale scour and deposition processes that lead to formation of features such as gravel bars and pools. It also does not simulate bank scour or the tendency for stream channels to migrate. The presence of bars, however, is typically associated with depositional reaches, and this association provides a means by which the sediment transport model can be linked to habitat conditions. Additionally, changes in sediment texture can directly affect spawning habitat, and the floodplain accretion rate can influence the rate of vegetative succession.

5.2.2.3.2 Channel Migration. Channel migration during flood events can damage levees or other flood-management structures and erode farmland. Channel migration is important to riparian ecology, especially in some reaches where active meandering occurs, because it creates areas of freshly deposited sediment needed for successful regeneration of early-succession riparian vegetation and associated wildlife habitat. Erosion of existing vegetated banks also introduces woody material into the river, which increases the structural diversity of fish habitat in the channel. Not all river reaches in the Central Valley have exhibited significant channel migration, even under natural conditions; however, migration is ecologically important wherever it does occur, and it contributes significantly to the availability of specific habitat types in these river basins.

For reasons previously described, channel migration will be described as a statistically averaged rate for an estimated zone along a management reach. Rates of migration will be estimated from empirical measurements of historical channel migration rates and from sensitivity analysis of migration models to parameters that would be affected by management measures considered in the Comprehensive Study. Historical channel locations and migration rates have been measured from historical maps and aerial photographs for most of the Sacramento and San Joaquin Rivers, and some work has been done to correlate historical channel migration with sediment texture, floodflow magnitude, and bank protection (Cepello pers. comm.). Channel migration models have also been developed that apply hydraulic and sediment transport equations to predict migration of short sets of river bends (Larsen 1998). Sensitivity analysis using such modeling will be used to further develop correlations between migration rates and channel geometry, flow rates, and bank or bed erodability (i.e., presence/absence of resistant geologic units or bank protection).

5.2.2.3.3 Channel and Floodplain Morphology. The two foregoing attributes, sediment texture and channel migration rate, will be used to infer effects of management measures on channel and floodplain morphology (i.e., unique floodplain features previously described). The presence of some floodplain morphological features (e.g., oxbow lakes and point bars) and their associated habitats depends on the rate of channel migration. Similarly, in some reaches the turnover rate of riparian vegetation and the proportions of vegetation in each seral (successional) stage will depend on the rate of channel migration.

Changes in sediment flux will tend to aggrade or degrade floodplain features as well as the channel itself. The digital topographic maps of existing conditions are sufficiently detailed to show topographic features that involve at least a few feet of relief, such as oxbow lakes, deeper ponds, sloughs, ditches, and large inchannel gravel bars; however, the sediment-transport and migration models are not capable of simulating the evolution of these individual features. Instead, the model user may be able to infer whether the rates of formation and decay of these features would be increased or decreased by a measure based on simulated changes in sediment transport and channel migration.

5.2.3 BIOLOGICAL ATTRIBUTES

The EFM will focus on physical processes and physical habitat characteristics that affect habitat value. Ecological processes involving biological interactions (e.g., competition, predation, and invasion) are clearly important but are exceedingly complex. These biological relationships are difficult to quantify and, in most cases, would be affected only indirectly by management measures. For the purposes of the EFM, biological attributes selected for simulating aquatic and terrestrial habitats have known relationships with physical habitat conditions and are representative of the needs of a large number of organisms. For aquatic habitats, appropriate attributes and relationships have been identified by focusing on two representative species whose physical habitat requirements are known and are believed to be similar to the requirements of many other species. For terrestrial habitats, relationships of physical conditions to vegetation community types providing habitat for all native riparian and wetland species are directly used. Because the EFM includes physical habitat variables relevant to most aquatic and terrestrial organisms, the model user can investigate habitat conditions for a single species simply by varying physical habitat variable values to reflect the requirements for that species.

5.2.3.1 Aquatic Habitats. For aquatic elements of the Sacramento and San Joaquin River basin ecosystems, discerning the multitude of biological attributes (i.e., energy and material transfer in its various trophic pathways; species diversity, abundance, and distribution) is an insurmountable task, even at a qualitative level. Two representative species, chinook salmon (*Oncorhynchus tshawytscha*) and splittail (*Pogonichthys macrolepidotus*), are sensitive to an important cross section of ecosystem attributes and provide needed focus for identifying biological attributes to include in the ecosystem model.

Chinook salmon and splittail are considered representative species because life stages of both species occur over extensive portions of the Sacramento and San Joaquin River basins. Both species are relatively high on the aquatic foodchain, so their status indirectly reflects the health of lower trophic levels. Chinook salmon and splittail are of particular interest to resource management agencies, and management objectives for the Comprehensive Study are assumed to be consistent with the objectives identified for these aquatic species by CALFED, the U.S. Fish and Wildlife Service (USFWS), and National Marine Fisheries Service (NMFS) (CALFED Bay-Delta Program 1998; U.S. Fish and Wildlife Service 1996, 1997; National Marine Fisheries Service 1997). Additionally, winter-run chinook salmon are listed as endangered under the state and federal ESAs (59 FR 440, January 4, 1992) and fall-, late fall-, and spring-run chinook salmon and splittail are proposed for listing (63 FR 11481, March 9, 1998; 59 FR 862, January 6, 1994). Chinook salmon also support important commercial and sport fisheries (Pacific Fisheries Management Council 1998).

Ecosystem attributes affecting splittail, chinook salmon, and other aquatic species are shown in Table 2. Reproduction, growth, and survival of splittail are particularly influenced by inundation of the floodplain (Sommer et al. 1997). Figure 3 illustrates conceptual relationships between physical and biological attributes important to reproduction, growth, channel migration, and survival of aquatic species. Relationships to be included in the EFM between physical attributes and biological attributes will reflect species occurrence and life-stage development relative to the magnitude, frequency, timing, duration, and rate of change in specific physical attributes.

Physical attributes important in floodplain areas are inundation and connectivity (i.e., the elevation of the hydraulic control between a temporarily connected water body and the main river channel). Inundated area is an important attribute that is easily measured and indicates potential spawning and rearing habitat abundance for aquatic species, including factors affecting food availability and access to diverse conditions (e.g., water temperature, substrate). Floodplain and floodbasin area is further divided by structural differences that provide diverse habitat components that may have variable importance, depending on seasonal availability and species needs. Connectivity determines access to potential floodplain and floodbasin habitat. Following inundation of the floodplain or floodbasin, continuing access to the river channel is important to survival, and subsequent maturation to the adult life stage, of many species.

Reproduction, growth, and survival of chinook salmon are strongly influenced by environmental conditions in the river channels of the Sacramento and San Joaquin River basins as well as by inundation of the floodplains and floodbasins (CALFED Bay-Delta Program 1998, U.S. Fish and Wildlife Service 1997, Sommer pers. comm.). Conceptual relationships between physical and biological attributes in the channel environment are similar to those for floodplains, except that bank type (e.g., shaded riverine aquatic, revetment), substrate texture, and hydraulic complexity within the channel are additional important factors.

The EFM developed for the Comprehensive Study will include only a subset of the complete spectrum of ecosystem attributes that affect chinook salmon, splittail, and other aquatic species. For example, the channel morphology attributes of pools, riffles, runs, and channel branching are governed by physical processes for which accurate quantitative models are not available. Small floodplain features will also be too small to simulate with available topographic information, although inundation and connectivity of larger floodplain features can be simulated.

We are not recommending that water temperature be universally simulated in the initial version of the EFM (although temperature should be used to help define habitat zones by assigning an annual temperature range for each management reach, based on existing conditions). In winter, the principal potential effect of management measures on water temperature would be the creation of localized areas of warmer water on inundated floodplains. However, simulating the distribution of warm areas and the amount of warming would require the use of two-dimensional hydrodynamics models coupled with energy balance models, which are not presently available. In summer, management measures that promote shoreline vegetation (shaded riverine aquatic cover) may slightly lower water temperatures in nearshore zones along the main river channels, but the effect in large rivers is small when compared with ambient temperature and effects of reservoir releases. However, new reservoirs or reservoir reoperation for flood control could significantly affect water temperatures in inundated reaches and reaches downstream of the reservoirs, which will warrant full evaluation of such effects in project planning reports. (See also “Future Model Refinement” below.)

5.2.3.2 Terrestrial Habitats. The diverse array of vegetation types found in the lowland alluvial river ecosystem will be simplified for the initial version of the EFM into the following habitat or cover types:

- open water,
- riverwash (freshly deposited sediment on gravel bars and along channel margins),
- marsh,
- woody riparian (several successional stages), and
- upland.

These categories of vegetation are easy to distinguish and they reflect a variable response to hydrologic conditions. Lists of species that commonly occur in each category will be prepared. In reality, the transitions between the community types are gradual because of overlapping environmental tolerances of species. Some species have relatively specific habitat requirements, while others have wider tolerances. Additionally, relatively specific environmental conditions (e.g., soil moisture) are necessary for germination and seedling growth of many species, whereas mature individuals can tolerate a wider range of conditions.

The effects of various physical ecosystem attributes on spatial and temporal transitions and transformations among habitat types are shown conceptually in Figure 4. Physical attributes selected for the EFM are described in Table 3 and include:

- soil texture;
- depth to groundwater;
- duration, frequency, and season of inundation;
- geomorphic/plant establishment dynamics; and
- plant-succession dynamics.

5.2.3.2.1 State Variables. The first three terrestrial habitat attributes address aspects of soil moisture availability. Soil texture affects the amount of water retained in the root zone following rain or inundation events and the magnitude of the capillary rise of moisture above the water table. Fine-grained (silty) soils provide suitable conditions for most woody riparian species. Very fine-grained soils (clays), usually in low topographic position, hold moisture tightly and tend to support marsh rather than woody riparian species.

The duration, frequency, and timing of inundation affect the extent and reliability of soil moisture replenishment before the summer dry season and are particularly important for seed dispersal, germination, and early growth of phreatophytic vegetation types. Moderate flood events (5- to 10-year events) are probably of greatest importance to plant establishment because they provide several opportunities during the lifespan of riparian trees for seed germination on soil surfaces that have been fully saturated but that are not frequently exposed to subsequent scouring events.

Variation in river stage and inundation also interacts with the flood-tolerance thresholds of plant species and vegetation community types. For example, rising stage and inundation of woody riparian species that have begun to photosynthesize in the atmospheric environment can kill the plants, although many of these same species are adapted to long periods of inundation during the wet season. As another example, relevant to community type, large areas in the downstream reaches of the river system have low topographic position and very low gradient; the combination of long inundation and very-fine-textured soils limits vegetation to marsh communities in these areas.

Groundwater provides a reliable source of water that is freely available to plants throughout the typical summer drought if they have roots that extend to the water table. These phreatophytes constitute the majority of trees and shrubs occupying the riparian zone. Depth to groundwater (moderated by capillary rise as affected by soil texture) therefore defines the extent of the *potential* riparian zone (the zone that could eventually be colonized) in the floodplain environment. Depth preferences exist for each phreatophyte species (moderated by soil texture) beyond which they grow poorly or cannot exist (e.g., Owens Valley riparian groundwater depth data analyzed by Ecosat Geobotanical Surveys, Inc. 1990 and summarized by Jones & Stokes Associates 1993), even if rainfall and seasonal inundation during plant establishment are optimal.

Water-table depth also affects the probability of successful regeneration for phreatophytes. Phreatophytes must survive on soil moisture from the date of germination until the roots have grown to reach the water table. If the depth to groundwater is large, the probability of sustaining sufficient soil moisture throughout this period—which can be several years—is relatively low. Thus, a potential riparian zone with a relatively deep water table may not be colonized for many decades (unless it is cultivated).

5.2.3.2.2 Process Variables. The two attributes reflecting the necessary dynamic character of a healthy ecosystem are geomorphic/plant establishment dynamics and plant-succession dynamics. The former functional attribute refers to the rate at which a migrating channel undercuts and removes areas with mature vegetation on the outside of bends while simultaneously depositing sediment that is colonized by riparian species on the inside of bends. Fresh alluvial deposits along a river channel favor the establishment of early-succession riparian species, such as willow and cottonwood, because those sites are usually sunny, close to the water table, and free of established competitors. Treatment of this attribute in the EFM was previously described under "Physical Attributes - Geomorphology".

Succession of vegetation from one community type to another is an important functional attribute of lowland alluvial river ecosystems as well. The EFM will indicate the average annual rate of change from one successional stage to another for the entire simulated reach of river and floodplain, based on historical observations of vegetation along Central Valley rivers. Rates of vegetative succession are variable along a given reach of river, and the timing and location of some of the factors affecting succession are difficult to predict; consequently, succession over time at specific locations will not be simulated explicitly in the initial version of the EFM. Instead, the EFM will combine the average annual channel migration rate and the typical rate of vegetative succession in healthy riparian systems to estimate the average amount of each successional stage within the simulated area over the long term.

The EFM will therefore produce maps of vegetation type resulting from a particular measure (state attributes), accompanied by data defining the estimated proportions of each successional stage over the long term (rate attributes) and this information will, in turn, indicate the total amount of each type of available habitat over the long term.

5.2.3.3. Terrestrial Wildlife. Habitat for most wildlife species in lowland alluvial river ecosystems is highly correlated with vegetation type and successional stage; therefore, wildlife attributes can largely be inferred from vegetation attributes simply by developing a table associating wildlife species with the vegetation types and successional stages included in the EFM. For example, early successional riparian forest may provide suitable habitat for species, such as the yellow warbler, that are associated with riparian shrubs and small trees but provides little or no habitat value for species associated with more mature riparian forests (e.g., the downy woodpecker). As the riparian vegetation matures, the suite of wildlife species associated with the habitat area would also change.

Wildlife are affected by more than just the total amount of each type of vegetation. Other factors that affect wildlife habitat include:

- vegetation patch size (i.e., the size of an area or "patch" that has one vegetation type and is surrounded by other vegetation types),
- vegetation patch shape (e.g., average width, area/perimeter ratio),
- vegetation patch continuity (percent of total length of channel or floodplain with continuous habitat),
- vegetation patch mosaic (the cumulative length of boundary between each possible combination of two adjoining habitat types or the total area of habitat types within a specified distance of each other),

- inundation of habitat, and
- agricultural crop type and associated management practices (e.g., irrigation practices).

5.2.3.3.1 Habitat Mosaic. The yellow-billed cuckoo is an example of wildlife affected by vegetation patch size. This species usually will not nest in stands of mature riparian forest that are less than 300 feet wide. Many other species also require minimum areas of contiguous habitat for the establishment of breeding territories. Continuity of riparian habitat along river channels is important to species such as mink, which forage and travel along the interface of riparian vegetation and stream channels. The degree of continuity directly affects the quality of riparian habitat that serves as migration, dispersal, and travel corridors for neotropical songbirds, mammals, and other species that require shrubs and trees as cover for their movements. The locations of vegetation types with respect to one another is important for species that make use of interfaces between vegetation types or that forage in one type and seek cover in another. For example, mallards prefer open patches of herbaceous vegetation for nesting, but also require nearby ponds or other suitable water bodies to successfully rear their young.

The EFM will use geographic information systems (GIS) software to statistically tabulate the patch and mosaic characteristics of vegetation types (not including successional phases) that result from the terrestrial habitat analyses previously described. Desirable patch characteristics for vegetation types simulated in the EFM will be estimated from relatively undisturbed riparian areas, as measured from 1930s aerial photographs. Patch characteristics will not be routinely calculated for individual wildlife species, although the model will be capable of providing this information if required.

5.2.3.3.2 Inundation Effects. Inundation affects wildlife directly, in addition to influencing the distribution of vegetation. Inundation for periods as brief as 1 day can cause substantial mortality of small mammals and ground-dwelling invertebrates but may have a limited effect on vegetation. For example, the giant garter snake hibernates near marshy areas and winter flooding of hibernation sites could drown individuals and suppress or eliminate populations in the affected area.

Seasonal flooding is beneficial for other species. For example, winter flooding of seasonal wetlands, pastures, and croplands can provide important foraging areas for some species of waterfowl that winter in the Central Valley, and spring/summer flooding can also provide waterfowl foraging and brood habitat during the breeding season. The EFM will evaluate inundation timing, duration, and frequency effects on selected wildlife species, in addition to assessing inundation effects on vegetation.

5.2.3.3.3 Agricultural Habitat Values. Agriculture can improve habitat for some species and displace habitat for others. Types of wildlife that benefit from agricultural lands include waterfowl, wintering and migrant shorebirds, and some raptor species. In the absence of the vast expanses of wetlands historically present in the Central Valley, resident and wintering waterfowl have become highly dependent on the high-quality forage provided by postharvest crop residue in corn, wheat, and rice fields and green forage produced in irrigated pastures. Agricultural fields that are saturated or flooded during early spring and late summer have also become important foraging areas for shorebirds that migrate through California. Raptors that historically foraged in Central Valley grassland and savanna habitats, such as the Swainson's hawk and white-tailed kite, are now largely dependent on agricultural lands as foraging habitat. Other species that are dependent on natural vegetation (e.g., woodpeckers and valley elderberry longhorn beetles [VELB]) are adversely affected when agriculture displaces natural vegetation. Beneficial and detrimental effects of agriculture on wildlife will be reflected in the process of superimposing land use factors to create actual habitat maps showing agricultural uses from potential natural habitat maps (see "Simulating Effects of Land Use" below).

5.2.3.3.4 Methods for Correlating Wildlife Attributes to Vegetation Attributes. Several methods are available for correlating wildlife attributes to vegetation attributes in the EFM. The method used will be dependent on the particular needs of EFM users; one method may provide a more accurate result than another depending on the nature of the query and the availability or precision of input to the EFM. In some instances, using a combination of methods may be required to achieve desired EFM outputs.

Habitat suitability index (HSI) models assign a numeric value to two or more important physical or biological variables on which a species is dependent or that characterize important structural functions of a community (e.g., percent emergent vegetation cover in a marsh). Numeric variable values are then mathematically combined to produce a single numeric index value that quantitatively describes the overall wildlife habitat value for a species or a community. Numerous HSI models have been developed by various agencies to describe physical and biological characteristics of the habitat needed or preferred by individual fish and wildlife species. A few HSI models have also been developed for wildlife or vegetation communities.

Table 4 lists several examples of existing habitat suitability models and the variables used in the models. Some variables, such as habitat patch area or width, will be direct outputs of the EFM. It may be possible that other variables, such as percent vegetative cover or average tree canopy height, which will not be simulated in the EFM, can be indirectly correlated with the age and seral stage of riparian vegetation. Variables that will be included in the EFM or that could possibly be indirectly estimated from EFM results are shown in boldface type in Table 4. Other variables are attributes that probably cannot be estimated from the EFM outputs because they involve small-scale features below the level of spatial resolution of the model or because they are primarily determined by biological processes that are not readily predictable. The EFM will therefore provide useful data for application of many existing HSI models, but it will not allow automatic application of more than a few of them. Other needed input variables for these HSI models would need to be estimated by traditional means, should investigators wish to apply these existing models. It may be possible, however, to develop modified habitat suitability models for these same species or communities that draw singularly from output variables of the EFM.

The California Department of Fish and Game's *Wildlife Habitat Relationships System* (Airola 1988) provides an additional means by which to infer habitat availability for individual terrestrial wildlife species from EFM results. This is a computerized database that links 880 terrestrial vertebrate species with the habitat types in which they are found, and the list of habitats includes categories and subcategories of riverine, riparian, wetland, and upland habitats that will be simulated in the EFM.

Yet another method for addressing habitat availability for individual species is to use *species-specific EFM queries* to vary the input data for the EFM to reflect the physical habitat criteria for the species. To the extent that variables included in the EFM are adequate to define the habitat for that species, the EFM will generate maps and tables describing the amount and distribution of habitat.

5.3 SIMULATING EFFECTS OF LAND USE

Simulation of the physical and biological processes described above will result in maps depicting state attributes and tables characterizing rate attributes, which together quantify the amount and location of various types of habitat in the absence of interference by land use activities; therefore, the initial EFM results will indicate "potential" habitat.

Land use overrides the natural habitat factors and imposes a type of habitat that is largely or entirely different from what would occur naturally. For example, cultivation of agricultural fields on floodplains displaces riparian forest that might naturally grow there but provides an alternative type of wildlife habitat (as previously described). Vegetation clearing in a floodway might alter the condition, age structure, or successional stage of vegetation without eliminating it entirely.

Land use must be considered in the model if a realistic evaluation of ecosystem health and floodplain habitat distribution is to be obtained. Furthermore, some of the management measures considered in the Comprehensive Study specifically involve land use activities, and the model must be capable of simulating their effects.

In the context of the EFM, land use is broadly defined to include any structures or human activities that alter or override physical or biological conditions at a given location in the terrestrial or aquatic parts of the ecosystem. It includes farming and ranching, urbanization, roads, bridges, dams, vegetation management, and pollution sources. Maps of "actual" habitat will be developed by superimposing the effects of land uses and related management measures on the maps of potential habitat. A digital land use map will be developed that shows cropland, orchards, grazing lands, urban areas, and floodway maintenance areas. The effect of land use on habitat value for various types of species and communities will be evaluated on a case-by-case basis and used in a map-screening process to modify the predicted habitat designations of the affected areas.

An exception to the above approach relates to bank protection. Although bank protection might fit the definition of "land use" as just described, bank protection will in fact be factored into the EFM element simulating channel migration, as previously described. Moreover, it can be assigned to a modified woody-riparian habitat type; therefore, effects of bank protection will be directly modeled in the EFM.

5.4 MODEL CALIBRATION AND ACCURACY

The accuracy of the EFM will be investigated during model calibration. If the assumptions, attributes, and functional relationships in the model have been correctly formulated, the EFM should be able to simulate the *existing* distribution of aquatic and riparian habitats reasonably well. It should also be able to correctly indicate the type and magnitude of habitat changes that resulted from historical alterations of flow and channel morphology. After an initial model has been developed, data representing existing conditions will be entered and the simulation results will be compared with existing habitat at selected locations throughout the Central Valley. Locations representing a variety of habitats will be investigated to evaluate the performance of all aspects of the model. Some of the simulated variables, such as total area of each type of habitat, can be readily tabulated and used to develop a quantitative measure of model accuracy. Other variables, such as vegetation patch shapes, may be more difficult to quantify. In any case, the comparisons will provide a qualitative indication of model accuracy that will be useful for interpreting simulations of future conditions; however, simulations of conditions that are beyond the range of conditions observed historically will be of unknown accuracy.

Comparisons of simulated and measured habitat distributions may lead to modifications of the functions initially included in the model (calibration) so that the EFM is as accurate as feasible given its purpose and the availability of supporting information. In the long term, an adaptive management approach to environmental restoration provide information that can be used to further refine and improve the model (see “Future Model Refinement” below).

6.0 MODEL OUTPUT AND INTERPRETATION

6.1 MODEL OUTPUT

Model output will consist of maps and tables comparing with- and without-action conditions, as follows:

- areas where physical and biological conditions are suitable for:
  - -- key aquatic species,
  - -- key terrestrial habitat types, and
- rates of ecosystem renewal.

A description of the specific outputs from the conceptual EFM is shown in Table 5. Model outputs constitute the selected indicators of the status of ecosystem attributes of concern. (See foregoing “Definition of Terms”). Table 5 lists each *ecosystem attribute* considered essential in characterizing the aquatic and terrestrial habitats of the lowland alluvial river systems and sensitive to the types of measures that may be applied (Table 1). Most importantly, Table 5 shows the measurable variables or *indicators* used in the model to represent each attribute of concern. The table also notes the *format* of each such output, whether a spatially depicted output (a map) or a numeric or descriptive comparison of proposed actions with baseline conditions (discussed in the following section).

The attributes (and corresponding indicators) in Table 5 are both state and rate (or process) variables. Rate variables reveal ecosystem dynamics, as previously discussed. Some attributes involve both state and rate, such as the suite of attributes that describe flow-velocity regime, inundation regime, or other seasonally varying parameters.

Some proposed indicators in Table 5 refer to types of data “relevant to” biological function, species, plant tolerances, etc. These indicators will require fuller definition during model development. Currently, physical and biological attributes have been identified that describe key physical variables or types of variables affecting habitat suitability and habitat dynamics. The precise relationships between them requires further evaluation. As an example, the inundation regime is considered key to both aquatic and terrestrial habitats, but the particular season, depth, and duration of inundation most appropriate to the selected indicator aquatic species and the major terrestrial habitat types require further definition. This subsequent definition will be based on both quantified data from the Central Valley or other lowland alluvial river-floodplain systems and on professional judgement of ecologists experienced in the Sacramento and San Joaquin River basins.

Map and numeric summary outputs as defined in Table 5 will use GIS mapping and summary reports. GIS provides the capability of simulating a wide range of spatial scales and allows automated processing of map data. The rapid turnaround afforded by GIS will allow multiple hypotheses or alternative project designs to be readily tested. This iterative capability will be essential to determining the sensitivity of model outputs to selected habitat-suitability criteria and in responding to comments from other concerned ecologists.

The use of modeling software permitting linking geographic display to real-time graphic simulations of varying flow conditions will not be included in the EFM. Presentation software could be developed as a future model refinement if it becomes essential to fostering public understanding and support for proposed actions.

6.2 INTERPRETATION OF MODEL OUTPUT

Interpretation of model output must be done in the context of the model’s purpose, which is to serve as an analysis tool to help identify, design, and assess appropriate and effective measures for flood-damage reduction and environmental restoration. The model may also be used to examine where information and understanding of interrelated ecosystem processes are weak; this should result in more relevant and applicable research. The model is intended to be a tool for comparing alternative measures, but future monitoring of results can help to improve the model’s accuracy in absolute terms.

The EFM will provide quantitative information about the effects of management measures on the amount, distribution, and dynamic nature of aquatic and terrestrial habitats. It will not directly indicate whether a particular management measure should be implemented. Such conclusions are subjective and constitute an interpretation that uses model results but is not determined by the model. To determine the degree to which a proposed measure is ecologically beneficial, a reference or comparison standard is needed for measuring the value of the habitat produced by the measure. For the purposes of the EFM, relatively undisturbed natural habitats will be used as the reference for measuring the desirable direction and relative magnitude of change of each output variable.

Choosing the appropriate amount of change requires a balancing of resources that is beyond the scope of the EFM. Answering questions such as "how much habitat is enough?" or "how much can we afford?" requires consideration of other important societal uses of river-floodplain systems, such as for water supply, flood control, food production, and recreation. In the Pacific Northwest, for example, the concept of a "normative condition" has been developed, which refers to the range of values of ecosystem indicators that reflect a healthy ecosystem supporting both natural and human values. It represents the healthiest ecosystem condition achievable, given assumed constraints. Interpretation of EFM results, including valuing, prioritizing, and ranking measures, will be performed by the Comprehensive Study cooperators in collaboration with affected stakeholders.

Simulation results for each management measure (and each design option), or for each alternative (combinations of measures), will be mapped, tabulated, and compared to simulated results for:

- current condition,
- future-without-action condition, and
- natural condition.

6.2.1 CURRENT AND FUTURE-WITHOUT-ACTION CONDITIONS

Both the current and the future-without-action conditions will be assumed to have the following characteristics:

- existing levee and bypass system configurations;
- existing channel geometries and planform;
- existing policies and funding levels for channel and levee maintenance;
- existing flood-control operating rules for reservoirs and bypass weirs;
- occasional flood-control-system failures and unwanted inundation; and
- climate patterns similar to recent historical patterns (i.e., no climate change).

The future-without-action condition, however, will assume additional conversion of natural banks to riprapped banks along the Sacramento River and its major tributaries.

6.2.2 NATURAL CONDITION

Historical or predevelopment conditions provide key information for establishing biological criteria defining a healthy ecosystem. Aerial photographs of relatively undisturbed riparian areas and historical reports describing fish and wildlife will be used to estimate attribute values indicative of a healthy ecosystem. Examples of ecosystem characteristics that can be gleaned from these sources include the suite of species present in a given habitat, proportional populations of those species, channel migration patterns and rates, and succession rates and relative proportions of seral vegetation stages.

7.0 MODEL DEVELOPMENT AND INFORMATION FLOW

A series of tasks is needed to translate the structural and functional attributes of the initial conceptual model described in the previous section into variables and equations of a mathematical model. An complete list of actual steps is presented in Appendix D, "EFM Modeling Tasks", which outlines in detail sources of data, types of existing software that may be used, and the specific computational steps involved in calculating the key ecosystem attribute parameters described in the preceding sections.

A flow diagram of the first three steps is shown in Figure 5. Steps involved in developing the hydraulic models are included only at a general level here but are described in detail in the draft work plan for the Hydrologic Engineering Management Plan (U.S. Army Corps of Engineers 1998).

The flow of information in the model can be divided into four primary steps, each of which involves a different kind of data manipulation and computer software.

- The first step involves simulation of both flood hydraulics (100-year to 1-year floodflow) and low-flow hydraulics in the river channels and development of stage-discharge relationships. This information will allow mapping of inundated area for any flow (which, as noted, is important for fish rearing and regeneration of riparian vegetation). These simulations will be done using hydraulics models such as HEC-2 and UNET and the new detailed topographic data. Sediment transport will be simulated using a HEC-6 model coupled to the hydraulics models.

- The second step involves evaluating the time series of daily flow data to estimate values of selected physical and biological indicators associated with particular durations and seasonal and annual frequencies. This step includes analyses of velocity, water depth, stage, inundation, and channel-migration regimes.

- The third step involves a map-screening analysis. Floodplains will be mapped for key flows selected after time-series analysis. Habitat criteria related to inundation, soil type, depth to groundwater, and land use will be applied to the basic data sets and processed by overlaying maps of the selected attributes. Existing conditions will therefore be simulated. All maps will be digital and will be stored and manipulated in a GIS.

- The fourth step is to develop changes to input parameters to represent various management measures and simulate the effects on indicators for habitat distribution and ecosystem dynamics and compare the results with the future-without-action and natural reference conditions, as well as with the study objectives (Appendix A).

When Study Team members have reached agreement on conceptual model design, a detailed work plan for constructing the model will be prepared. Key tasks will include development and quantification of ecological relationships identified in the conceptual model and development of the computer programs and software links needed to implement the model (as described in Appendix D).

8.0 POTENTIAL FOR FUTURE MODEL REFINEMENT

The EFM may be improved through an iterative process of model development, monitoring, and model refinement. The EFM for the Comprehensive Study is being developed using hypotheses about the response of ecosystem attributes to flood-damage-reduction and environmental restoration measures. Monitoring implemented measures provides an opportunity to observe actual environmental responses and could help verify the accuracy of the model and guide refinements that would improve the ability of the model to describe and predict ecosystem response to specific measures. A monitoring program could also guide adaptive management, where such an approach is adopted. Areas that might be fruitful for future model refinement include the following::

- **Simulate Water Temperature.** Simulation of water temperature is not included at this time because of the relatively indirect relationship between flood damage reduction measures and water temperature in most cases. If measures are proposed that might significantly affect summer water temperatures (e.g., new reservoirs or substantial reservoir reoperation), the EFM could be enhanced to consider water temperature. Alternatively, a separate temperature model could be developed for temperature-sensitive reaches likely to be affected by the proposed measure. Daily streamflow temperature models for the network of river channels, bypasses, floodplains, and floodbasins could be developed using hydraulics and channel geometry data from the hydraulics models and meteorological data from California Irrigation Management Information System (CIMIS) stations. The JSATEMP spreadsheet model could be expanded to incorporate flow splits and convergences so that all waterways could be simulated simultaneously.

- **Include New Biological Information and Additional Attributes.** A limitation of the initial EFM is the amount of data available for quantifying relationships among attributes. Information regarding ecological functions that is generated through monitoring programs could be incorporated into the model in the future. Incorporating

  new information as it becomes available would enhance the model and could improve its effectiveness as a planning and management tool.

- **Incorporate Spatial-Temporal Channel Migration Models.** Models capable of simulating the timing, amount, and location of migration of a given river channel and flow time series may become available in the future. Incorporating those models into the EFM could allow map-based analysis of channel migration and vegetative succession, rather than statistical and tabular analyses that will be employed in the initial EFM.

9.0 CITATIONS

9.1 PRINTED REFERENCES

Airola, D. A. 1988. Guide to the California wildlife habitat relationships system. Prepared for California Department of Fish and Game. Rancho Cordova, CA. Jones & Stokes Associates. Sacramento, CA.

Allen, A. W. 1987. Habitat suitability index models: gray squirrel. Biological Report 82(10.135 revised). U.S. Fish and Wildlife Service. Fort Collins, CO.

Bovee, K. D. 1982. A guide to stream habitat analysis using the instream flow incremental methodology. June. (Instream Flow Information Paper No. 12.) U S. Fish and Wildlife Service. Washington, D.C.

Caicco, S. L. 1996. RIPVEG, Version 1.0. August 22, 1996. U.S. Fish and Wildlife Service. Sacramento, CA.

CALFED Bay-Delta Program. 1998. Ecosystem restoration program plan. Draft. Volumes I and II. Sacramento, CA.

Ecosat Geobotanical Surveys, Inc. 1990. Survey of vegetation of Owens Valley, California. Results of field and aerial photo interpretation following 17 years of water management activities. North Vancouver, BC, Canada. Prepared for E.I.P. Associates, San Francisco, CA.

Fris, M. B. and R. W. DeHaven. 1993. A community-based habitat suitability index model for shaded riverine aquatic cover, selected reaches of the Sacramento River system. February. U.S. Fish and Wildlife Service. Sacramento, CA.

Garrison, B. A. 1988. Draft habitat suitability index model, greater yellowlegs (*Tringa melanoleuca*). March. U.S. Fish and Wildlife Service. Sacramento, CA.

Harwood, D. S., and E. J. Helley. 1985. Geologic map of the late Cenozoic deposits of the Sacramento Valley and northern Sierran foothills, California. Map MF-1790. U.S. Geological

Survey. Washington, DC.

Jones & Stokes Associates, Inc. 1991. Draft habitat evaluation procedures report for the Delta Wetlands project, appendices. January. (JSA 97-119.) Sacramento, CA. Prepared for State Water Resources Control Board, Sacramento, CA.

__________. 1993. Draft environmental impact report for review of Mono Basin Water Rights of the City of Los Angeles, Volume 1 and Appendix P. Sacramento, California. Prepared for Calfiornia State Water Resources Control Board, Division of Water Rights.

__________. 1998. Analysis of physical processes and riparian habitat potential of the San Joaquin River, Friant Dam to the Merced River). Sacramento, CA

Larsen, E. W. 1998. Modeling meander migration and bank erosion of the upper Sacramento River. in California watersheds: floodplain management and habitat conservation. University of California Extension. Davis, CA.

Lestelle, L. C., L. E. Mobrand, J. A. Lichatowich, and T. S. Vogel. 1996. Applied ecosystem analysis - a primer; the ecosystem diagnosis and treatment method. U.S. Department of Energy, Bonneville Power Administration. Portland, OR.

Levy, K., T. F. Young, R. M. Fujita, and W. Alevizon. 1996. Restoration of the San Francisco Bay-Delta-River system: choosing indicators of ecological integrity. Center for Sustainable Resource Development, University of California, Berkeley. Berkeley, CA.

National Marine Fisheries Service. 1997. Draft recovery plan for winter-run chinook salmon. Santa Rosa, CA.

Nestler, J. M., L. T. Schneider, D. C. Latka, and P. N. Johnson. 1995. Physical habitat analysis using the Riverine Community Habitat Assessment and Restoration Concept (RCHARC): Missouri River case history. May. (Technical Report EL-95-18.) U.S. Army Corps of Engineers, Environmental Impact Research Program. Washington, DC.

Pacific Fisheries Management Council. 1998. Review of 1997 ocean salmon fisheries. Portland, OR.

Peters, M. R., S. R. Abt, C. C. Watson, J. C. Fischenich, and J. M. Nestler. 1995. Assessment of restored riverine habitat using RCHARC. August. Water Resources Bulletin 31(4):745-752.

Roberts, R. C. 1986. Habitat suitability index model, riparian songbird guild, Humboldt Bay, California. August. Oscar Larson & Associates. Eureka, CA. Prepared for California State Coastal Conservancy and Humboldt County Department of Public Works, Eureka, CA.

Schroeder, R. L. 1982. Habitat suitability index models: yellow warbler. July. U.S. Fish and

Wildlife Service. Fort Collins, CO.

__________. 1983. Habitat suitability index models: downy woodpecker. April. U.S. Fish and Wildlife Service. Fort Collins, CO.

Sommer, T., R. Baxter, and B. Herbold. 1997. Resilence of splittail in the Sacramento-San Joaquin estuary. Transactions of the American Fisheries Society 126:961-976.

Tennant, D. L. 1976. Instream flow regimes for fish, wildlife, recreation, and related environmental resources. Pages 359-373 in J.F. Orsborn and C.H. Allman (eds.), Instream flow needs, Volume II. American Fisheries Society. Bethesda, MD.

U.S. Army Corps of Engineers, Sacramento District. 1998. Hydrologic engineering management plan - Sacramento River watershed management study, California. Sacramento, CA

U.S. Fish and Wildlife Service. 1985a. Draft habitat suitability index model, short-eared owl (*Asio flammeus*) wintering habitat in the Central Valley. June. Sacramento, CA.

__________. 1985b. Habitat suitability index model, northern oriole (*Icterus spurius*) breeding habitat, Central Valley, California. July. Sacramento, CA.

__________. 1987. Habitat suitability index models: marsh wren. June. Biological Report 82(10.139). Washington, DC.

__________. 1996. Recovery plan for the Sacramento/San Joaquin Delta native fishes. Portland, OR.

__________. 1997. Revised draft restoration plan for the anadromous fish restoration program: a plan to increase natural production of anadromous fish in the Central Valley of California. Portland, OR.

Warren, C. E. 1971. Biology and water pollution control. W. B. Saunders Company, Philadelphia, PA.

Young. T. 1997. Conceptual framework for indicator development: development of key ecological attributes for the San Francisco Bay-Delta watershed in Interagency Ecological Program Newsletter, Spring 1998.

9.2 PERSONAL COMMUNICATIONS

Cepello, Stacey. Environmental specialist. California Department of Water Resources, Northern District. May 14, 1998 - telephone conversation.

Greco, Stephen. Research specialist. Department of Biology, University of California, Davis. June 8, 1998 - meeting.

Larsen, Eric. Postdoctoral researcher. Department of Geology, University of California, Davis. June 15, 1998 - telephone conversation.

Sommer, Ted. Fisheries biologist. California Department of Water Resources, Sacramento. November 5, 1998 - meeting.

Table 1. Types of Management Measures under Consideration

A. Measures Affecting Floodflow Regime

- A1. Create or modify existing reservoir storage/releases
- A2. Create or modify transient storage in basins
- A3. Implement other measures affecting flow regime

B. Measures Affecting Conveyance Capacity

- B1. Set back levee
- B2. Reconstruct channel
- B3. Raise levee
- B4. Improve or create bypass system
- B5. Create meander belt
- B6. Manage vegetation/substrate within existing floodway
- B7. Implement other measures affecting flow capacity
- **. Construct backup levee
- **. Remove levee

C. Measures Affecting System Reliability

- C1. Protect streambank
- C2. Strengthen or repair levee
- C3. Remove bank protection
- C4. Implement other actions to increase system reliability

D. Measures Affecting Floodplain Management

- D1. Modify existing development to reduce future damage
- D2. Discourage future development in floodplains
- D3. Redirect incompatible development out of floodway or floodplain

---

** Comprehensive Study database number not yet available.

Table 2. Ecosystem Attributes Important to Aquatic Species

Aquatic Ecosystem	Attribute	Indicator
River Channel	Flow velocity-depth regime	Seasonal velocities/depths
	Channel morphology	Branching, meander, pool-riffle-run ratios
	Water temperature	Length[1]
	Bank type	Length and habitat quality of revetted bank or shaded riverine aquatic cover
	Substrate	Type, particle-size distribution
Floodplain/Floodbasin	Inundation regime	Flooded area of each habitat type (e.g., riparian forest, marsh, field) for specified timing, duration, and frequency
	Connectivity[2]	Duration and depth of the water connection
	Presence of permanent open water (e.g., sloughs, embayments, oxbows, side channels, borrow pits, ponds)	Depth, area

Notes:

1 Water temperature conditions are measured by the length of river channel where water temperature meets the needs of specific life stages of selected species, guilds, or communities.

2 Connectivity refers to opportunity for fish to use temporary habitat and return to the main river channel. The depth and duration of a water connection between temporarily inundated habitat and the main channel depends on river stage, elevation of the hydraulic control, storage volume of the temporarily inundated area, and cross-sectional area of the connecting channel. Movement of fish through the water connection depends on water velocity, water temperature, cover, depth, and the bottom elevation of the offchannel water body.

Table 3. Selected Ecosystem Attributes for Terrestrial Habitats

Attribute	Indicators	Applicable Habitat Types
Soil type suitable for each habitat type	Acreage, based on soil texture, as derived from Quaternary geology map units[1]	Riverwash (Qsc), woody riparian (Qa and Pleistocene-aged Qs), marsh (Qb), uplands (other)
Groundwater depth suitable for each habitat type	Acreages based on elevation difference between ground surface and average low-flow water surface[2]	Woody riparian, marsh, upland
Inundation duration, frequency, and season suitable for each habitat type	Acreages based on synthesis from detailed topography (both channel and floodplain), stream hydrology (various return-period flows and seasonal hydrographs from the historical record), and available[3] hydrologic-hydraulic relationships	Woody riparian, marsh, upland
Geomorphic/plant establishment dynamics	Rate of habitat acreage change based on predicted rate of channel migration from historical data and migration-model simulations[4]	Woody riparian, marsh, riverwash
Plant-succession dynamics	Rate of habitat acreage change based on synthesis of observed vegetation-succession rates with rate of channel migration[5]	Woody riparian

Notes:

1 Harwood and Helley 1985 provides coverage of the northern San Joaquin River basin and Sacramento River basin. Other quaternary geologic mapping or 1:100,000 historical soil surveys can be used to extend this information to the southern San Joaquin River basin.

2 Assumes relatively flat water table in nearstream area. This assumption should be verified wherever possible using existing groundwater surface approximations (available for some streams) or well-log data.

3 In the first phase of the EFM, normal-depth calculations (i.e., applications of Manning's law) can be used to approximate the relationship between flow and water-surface elevation. On completion of H&H models, a more refined relationship will be available.

4 Historical planform data is available from most of the river system and additional data may be developed. Historical data will require interpretation by an engineering geomorphologist based on current and projected flow regime, extent of resistant geologic formations (Harwood and Helley 1985), and existing or future bank protection. In addition, Larsen has developed a meander migration model that may prove useful in estimating future rates of channel migration (Larsen pers. comm.).

5 Typical succession rates can be inferred from surveys of historical vegetation change, such as studies by Greco for the meandering reach of the Sacramento River (Greco pers. comm.) and recent studies by Jones & Stokes Associates for the middle reach of the San Joaquin River (Jones & Stokes Associates 1998).

Table 4. Habitat Suitability and Ecosystem Models Applicable to Aquatic and Riparian Habitats in California's Central Valley (Page 1 of 4)

Model Name and Source	Species or Community	Variables[1]	Limitations and Remarks
HSI[2] (Garrison 1988)	Greater yellowlegs	1. Wetland water depth <7 in 2. Wetland water depth <3 in 3. Emergent vegetation height (<3 in) 4. Emergent vegetation cover (%)	Seasonal habitat for adults
HSI (USFWS 1987)	Marsh wren	**1. Marsh area >0.40 ha** 2. Growth form of emergent vegetation 3. Emergent vegetation cover (%) 4. Water depth (0-40 cm) 5. Woody vegetation cover (%)	Entire northern United States Breeding season habitat (spring-summer)
HSI (USFWS 1985b)	Northern oriole	**1. Deciduous tree canopy height (ft)** **2. Deciduous tree crown cover (%)** **3. Riparian woodland stand width (ft)**	Breeding habitat in Central Valley
HSI (Schroeder 1982)	Yellow warbler	**1. Deciduous shrub crown cover (%)** **2. Deciduous shrub canopy height (ft)** 3. Hydrophytic shrubs (%)	
HSI (Roberts 1986)	Riparian songbird guild	**1. Shrub (1-3 m) canopy cover (%)** **2. Tree (>3 m) canopy cover (%)** 3. Average height of overstory trees (m) 4. Canopy layering category 5. Large snag density (number per acre) 6. Woody riparian vegetation present (% of site)	

Model Name and Source	Species or Community	Variables[1]	Limitations and Remarks
HSI (Allen 1987)	Western gray squirrel	1. Canopy closure of mast-bearing trees 2. Density of leaf-litter layer **3. Tree canopy cover (%)** 4. Number of large trees per acre (>15 in dbh) **5. Minimum habitat area > 1 ac**	
HSI (Jones & Stokes Associates 1991)	California vole	1. Herbaceous cover (%) 2. Average herbaceous cover height (in) **3. Foraging habitat suitability (crop type)** **4. Distance from suitable refugia (relatively undisturbed cover) (mi)**	For Sacramento-San Joaquin Delta
HSI (Schroeder 1983)	Downy woodpecker	**1. Total basal area of trees** 2. Number of snags > 6 in in diameter **3. Minimum habitat area >10 ac**	
HSI (USFWS 1985a)	Short-eared owl	1. Herbaceous cover (%) 2. Herbaceous cover preferred by California vole (%) 3. Herbaceous vegetation average height (ft) 4. Vegetative diversity of marsh 5. Overwinter management practices for grain and sugar beet crops 6. Extent of rodenticide use (%)	Wintering habitat in Central Valley

Model Name and Source	Species or Community	Variables[1]	Limitations and Remarks
HSI (Fris and DeHaven 1993)	Shaded riverine aquatic (SRA) habitat	1. Overhanging cover at river's edge (% of SRA area) 2. Instream cover (% of SRA area) 3. Instream cover type (cobble, boulder, woody debris, undercut banks, aquatic vegetation) **4. Riverbed sediment texture (dominant grain size in mm)**	SRA area extends from the mean high-water line streamward to maximum extent of overhanging or instream cover Emphasis on salmonid fry and juveniles, belted kingfisher, and aquatic invertebrates Data assumed to be collected at mean summer flow
PHABSIM (Bovee 1982)	Salmonid fish	**1. Water depth (ft)** **2. Water velocity (ft/sec)** **3. Riverbed substrate texture** 4. Cover (boulder, woody debris, undercut banks, overhanging vegetation)	Distinguishes different needs at different life stages Relies on fish preference, not full range of tolerance Index normally calculated for "cells" (narrow width increments extending between cross sections)
Tennant Method (Tennant 1976)	Fish	**1. Mean annual flow**	Originally intended for trout in Montana Minimum recommended flow specified as a percent of mean annual flow No consideration of season or life stage

Model Name and Source	Species or Community	Variables[1]	Limitations and Remarks
RIPVEG (Caicco 1996)	Cottonwood forest Yellow warbler Northern oriole Wilson's warbler Western gray squirrel Downy woodpecker	**1. Mean flow from Mar through Oct for each year of record**	Cottonwood growth model based on lower American River data Cottonwood diameter growth rate a linear function of mean Mar-Oct flow Dynamic: as forest grows, it transitions to new classifications in California Wildlife Habitat Relationships System
Riverine Community Habitat Assessment and Restoration Concept (RCHARC) (Nestler et al. 1995, Peters et al. 1995)	Fish communities	**1. Cumulative distribution of depth-velocity combinations in a river reach at a given flow level**	Developed for Missouri River Assumes spatial variability in depth-velocity combinations strongly influences fish habitat suitability Typically uses 20 points across river width for ≥10 cross sections spaced 3-5 channel widths apart Typically applied to a small number of flows (e.g., two). No timeseries analysis of timing, frequency, duration, sequence

Notes:

[1] Variables highlighted in **boldface** type are those that will be simulated in the EFM or that are probably correlated with variables in the EFM.

[2] Habitat Suitability Index model

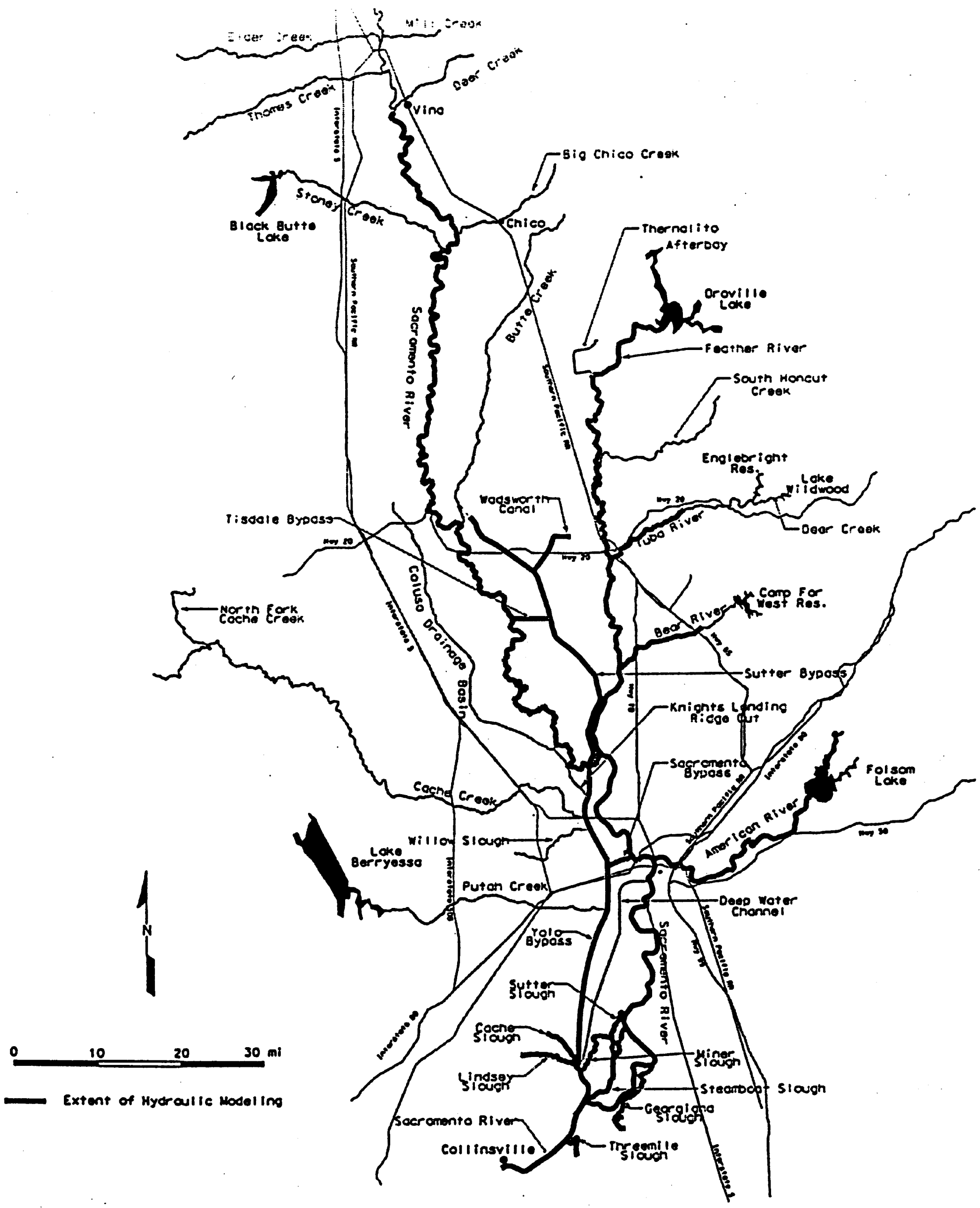
Table 5. Indicators: Ecosystem Function Model Outputs (Page 1 of 2)

Ecosystem Attribute	Model Output (Indicators)	Output Format[1]
Aquatic Habitat		
Extent and diversity of freshwater aquatic habitats (permanent and seasonal)	Predicted extent, number, and acreage	Maps and numeric comparisons
Flow-velocity regime for channels and overbank areas	Seasonal average and exceedance velocity estimates relevant to aquatic organisms	Numeric comparisons
Inundation regime for overbank areas	Distribution of floodplain inundation for various combinations of timing, duration, and frequency relevant to biological function	Maps and numeric comparisons
Connectivity of floodplain aquatic features	Depth-duration data for various connections	Numeric comparison
Bank type	Relative lengths of various bank types (e.g., revetted, natural) and relative ecosystem value	Numeric comparison
Instream cover input	Average annual acreage subject to channel migration	Numeric comparison
Channel substrate	Change in average gradation	Numeric comparison
Channel morphology and stability	Tendency toward channel and floodplain aggradation or degradation	Descriptive comparison
Terrestrial Habitat		
Topography	Topographic maps, range and distribution of slope angles, and presence of floodplain features	Maps and numeric comparisons
Floodplain inundation regime	Distribution of floodplain inundation for various combinations of timing, duration, and frequency relevant to biological function (i.e., plant establishment, plant survival)	Maps and numeric comparisons
Floodplain soil type	Distribution of soil types relevant to plant establishment and growth	Maps and numeric comparisons
Depth to groundwater	Distribution of areas where seasonal high and low water tables allow plant regeneration and survival	Maps and numeric comparisons

Ecosystem Attribute	Model Output (Indicators)	Output Format[1]
Potential terrestrial vegetation habitat (several types and seral stages, including regeneration)	Distribution of combined topographic, substrate, inundation, and groundwater conditions relevant to plant tolerances	Maps and numeric comparisons
Vegetation renewal and succession rate	Average annual acreage subject to channel migration, and proportions of each seral stage	Numeric comparison
Potential wildlife habitat	Vegetation patch and mosaic characteristics relevant to selected species or communities	Numeric comparison
Actual vegetation and wildlife habitat	Amount and distribution of habitats as affected by land use	Maps and numeric comparisons

Notes:

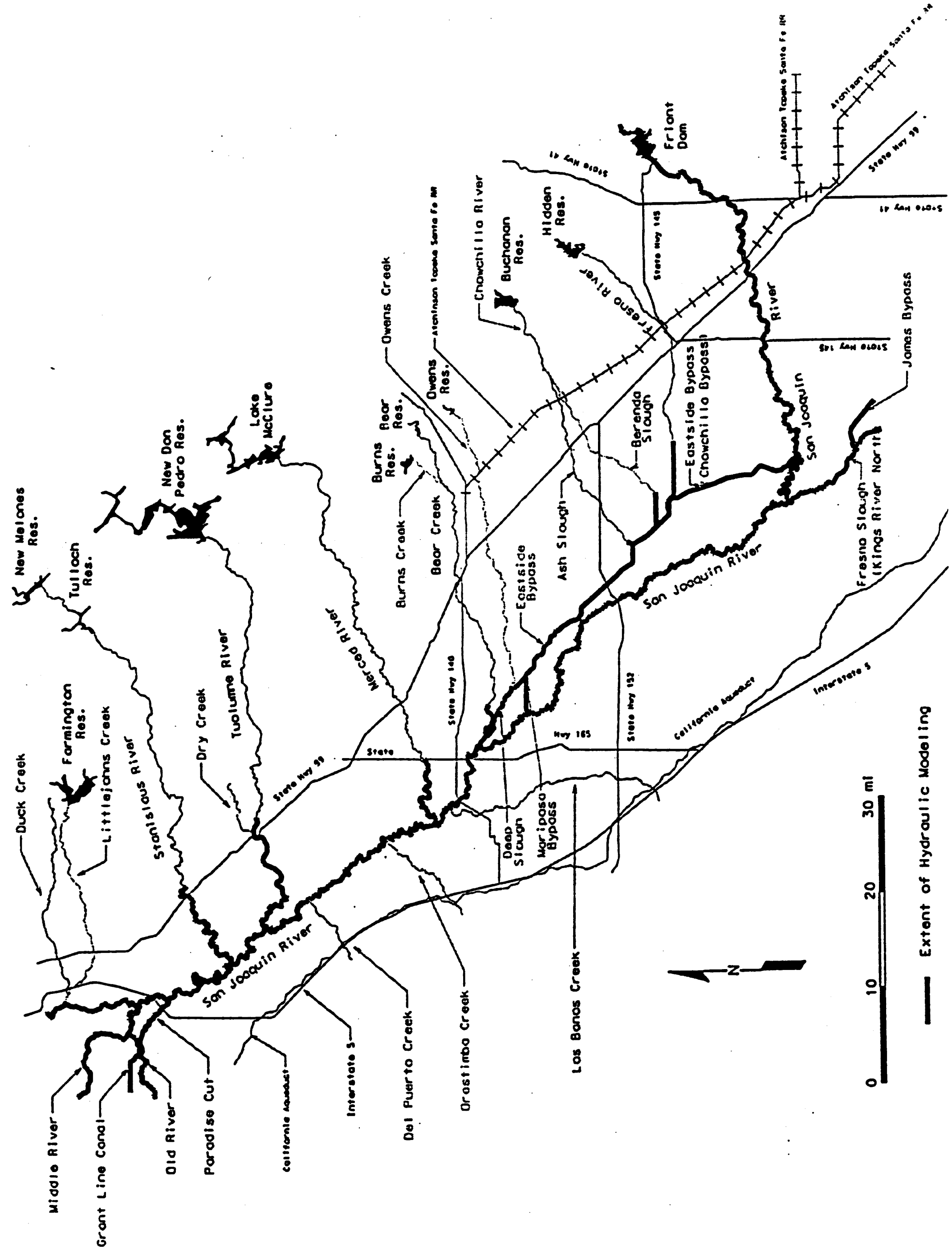
[1] Maps will be digital maps showing the distribution of habitats on the landscape. Numeric comparisons will consist of tables of total availability of each habitat type (acres) and statistics describing patch and mosaic characteristics.



Source: US Army Corps of Engineers.

Jones & Stokes Associates, Inc.

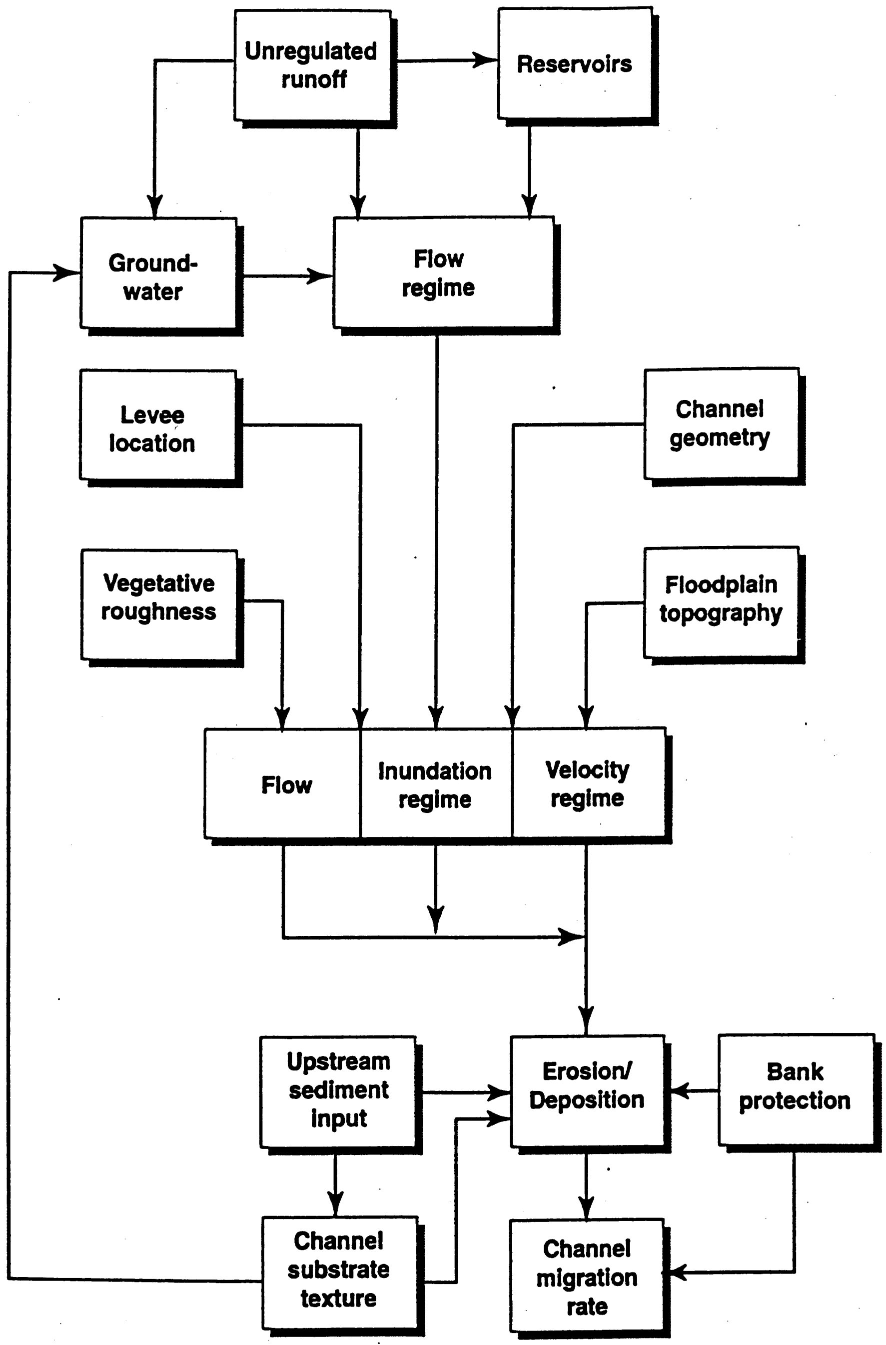
Figure 1A
Sacramento River Basin
Extent of Hydraulic Modeling



Source: US Army Corps of Engineers.

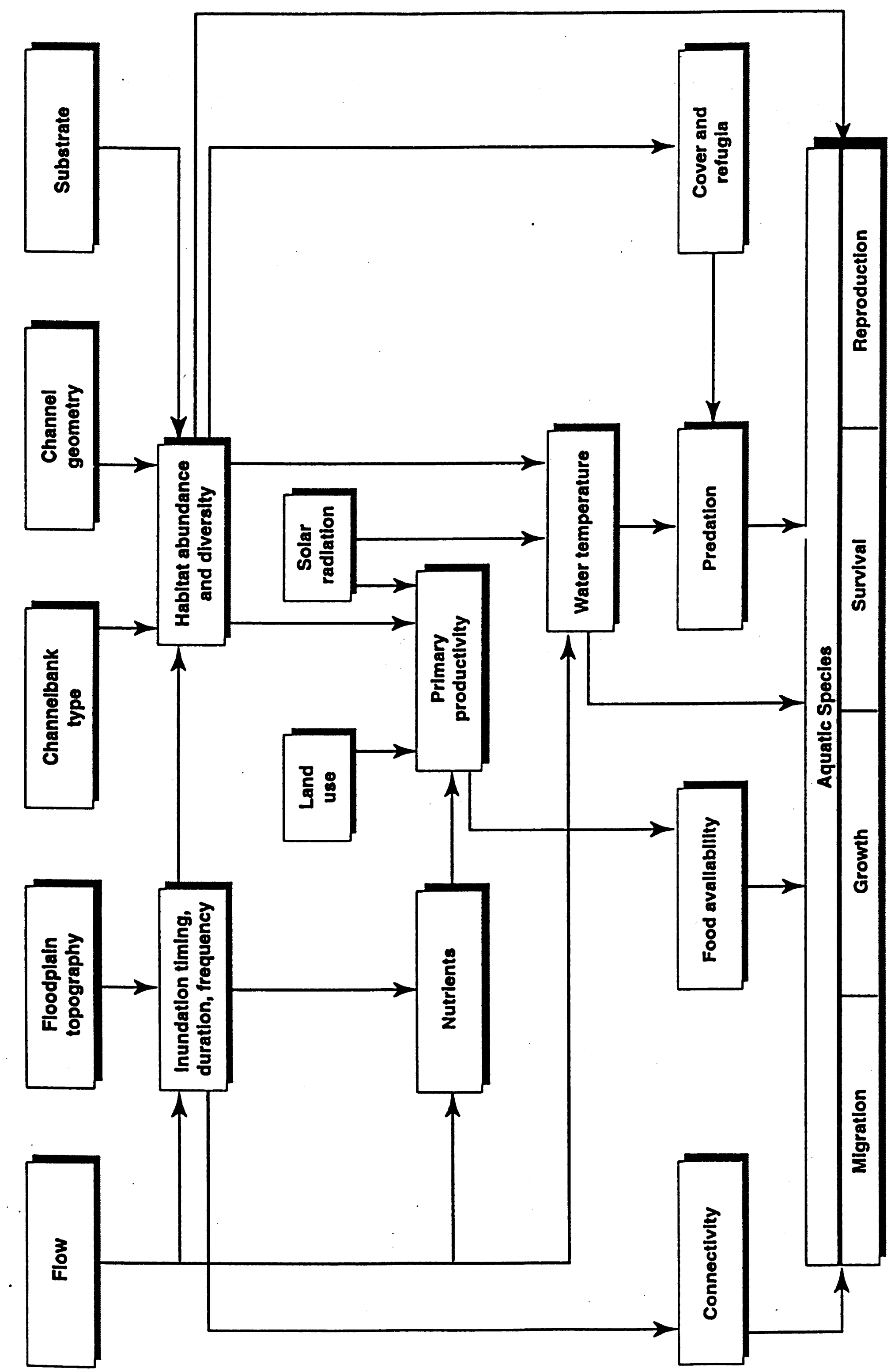
Jones & Stokes Associates, Inc.

Figure 1B
San Joaquin River Basin
Extent of Hydraulic Modeling



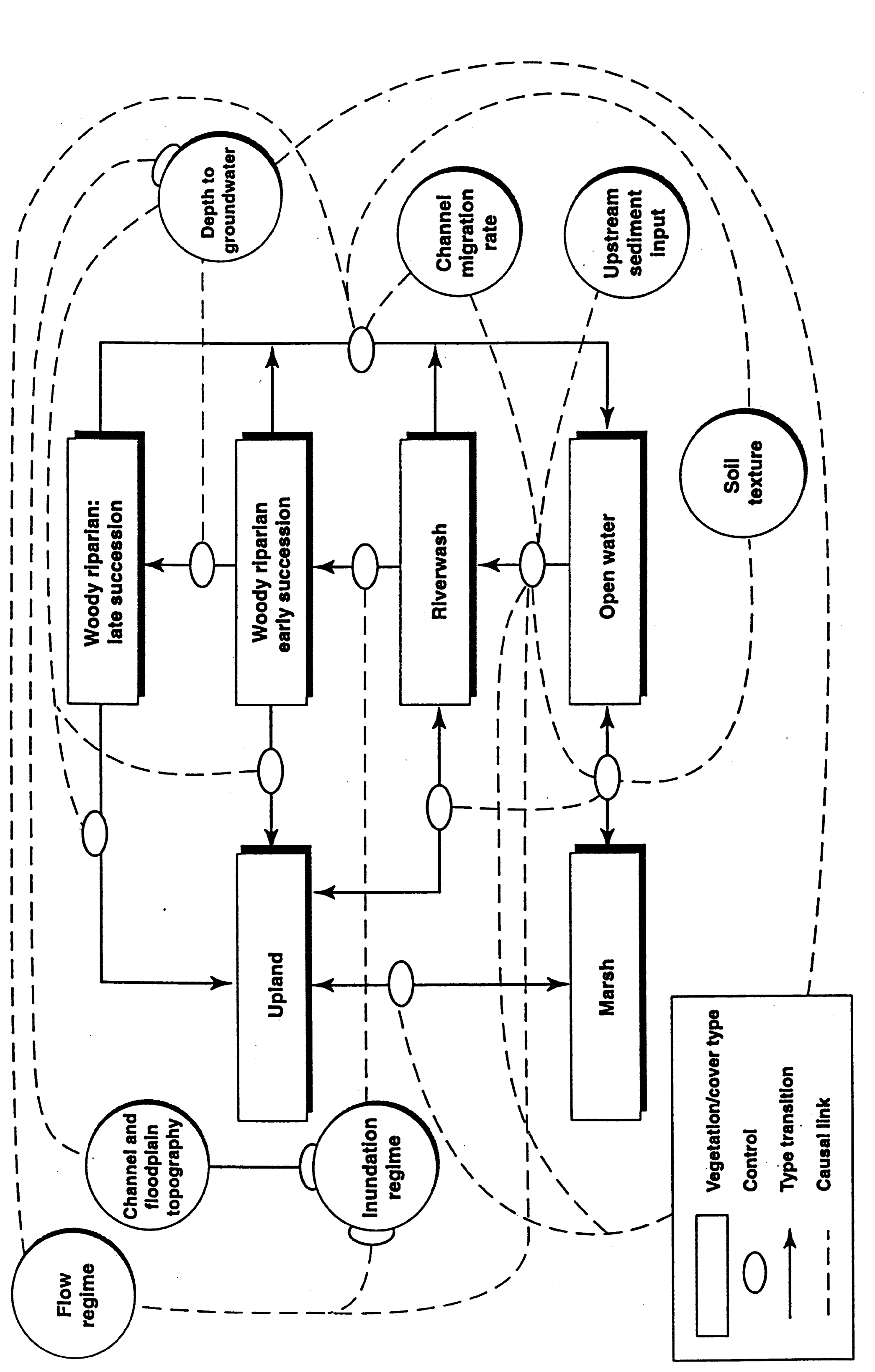
Jones & Stokes Associates, Inc.

Figure 2
Conceptual Model of Key Physical Processes in Lowland Alluvial River Ecosystems



Jones & Stokes Associates, Inc.

Figure 3
Conceptual Model of the Effects of Selected Physical Ecosystem Attributes on Aquatic Species



Jones & Stokes Associates, Inc.

Figure 4
Conceptual Model of the Effects of Selected Physical Ecosystem Attributes on Terrestrial Habitats

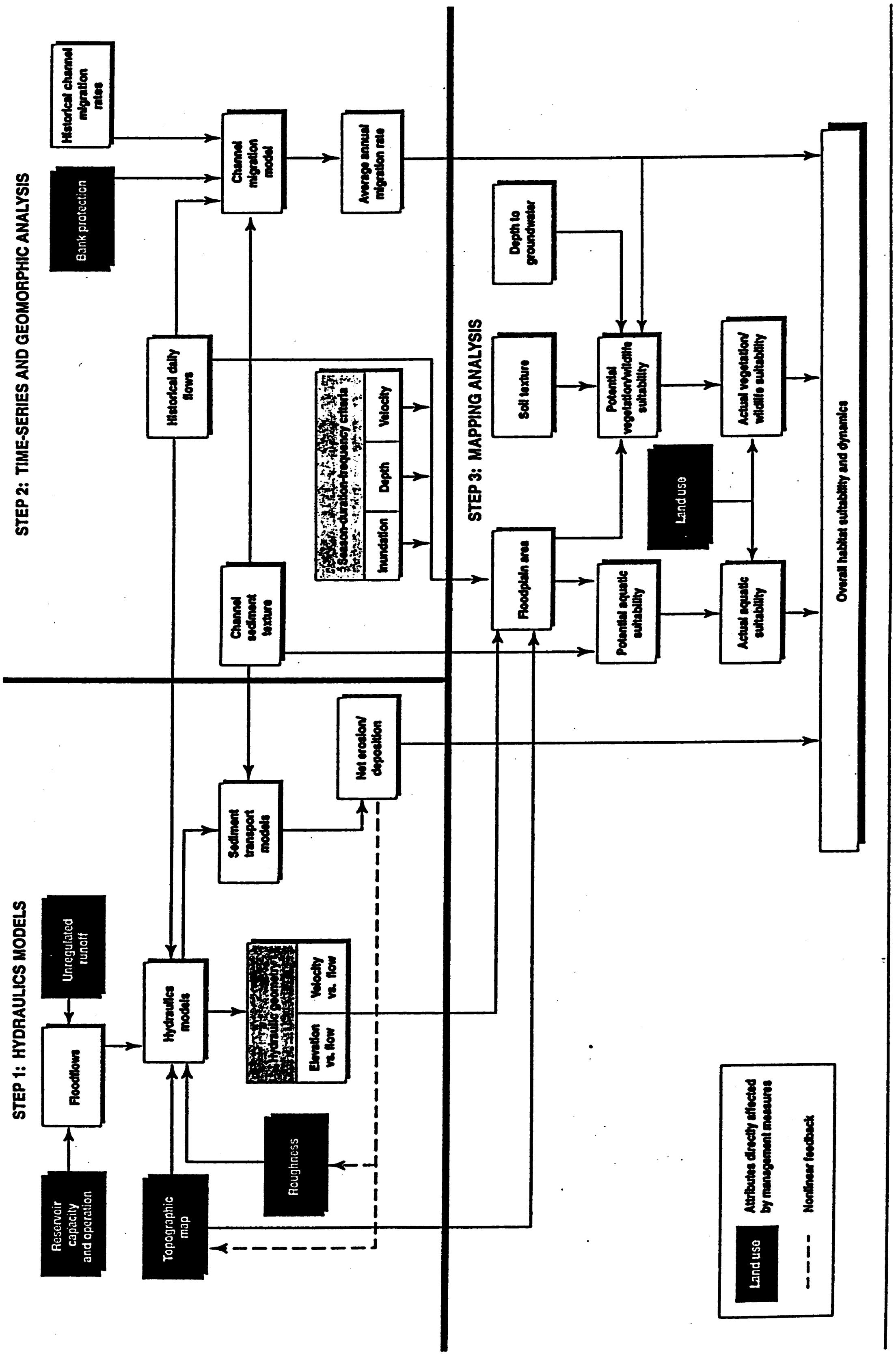


Figure 5
Flowchart of Information and Calculations in the Ecosystem Functions Model

Appendix A. Draft Planning Objectives for the Sacramento-San Joaquin River Basins Comprehensive Study

Problem statements and planning objectives for the Comprehensive Study were drafted by the study's planning team and executive committee. The statements and objectives reflect the intent of the Comprehensive Study authorizing legislation, input from technical support teams, recommendations from other agencies and organizations, and past experience with flood management in the Central Valley. The objectives are intended to address the identified flood management and ecosystem problems in the two river basins and will be used to evaluate the suitability of potential management measures.

SACRAMENTO RIVER BASIN PLANNING OBJECTIVES

Improve Flood Management Throughout the Sacramento River Flood Management System

- Identify flood-protection-level goals for the various parts of the system, taking into account the associated flood risk and the engineering, economic, and environmental feasibility of providing protection.
- Reduce the risk to lives and property by improving system reliability.
- Reduce the risk of catastrophic flooding to urban areas.
- Minimize flood-management-system operation and maintenance requirements and associated costs.
- Avoid or reduce potential future flood damages by communicating information about residual flood risk throughout the flood management system.
- Develop tools to analyze the hydrologic, hydraulic, geomorphic, and biologic processes of the flood management system.
- Improve systemwide coordination of floodplain management activities among local, state, and federal entities.

- Allow for adapting the system management in response to changes over time.

- Compensate for unavoidable adverse socioeconomic, land use, and environmental impacts associated with flood management actions.

Protect and Restore Riparian, Riverine, and Wetlands Habitats Systemwide

- Increase and improve riparian, floodplain, floodbasin, and riverine habitats throughout the Sacramento River flood management system using an ecosystem approach.

- Promote the stability of native species populations and recovery of threatened and endangered species in the flood management system.

- Promote natural, dynamic, hydrologic, and geomorphic processes in the flood management system.

- Preserve agricultural productivity while promoting the ecological value of agricultural land.

- Incorporate environmental restoration features into the design of federal, state, and local elements of the Sacramento River flood management system.

Resolve Policy Issues and Remove Institutional Barriers

- Develop evaluation criteria and a funding process that maximizes partnering potentials to implement needed system features.

- Implement improved floodplain management policies consistent with recommendations made by the Governor’s Flood Emergency Action Team (FEAT) report on floodplain management.

- Proceed with immediately implementable solutions to identified problems when consensus is reached.

- Improve flood-damage-reduction management and environmental permitting procedures to minimize and resolve conflicts.

SAN JOAQUIN RIVER BASIN PLANNING OBJECTIVES

Reduce Flood Damages, Risk of Levee Failure, and Maintenance Costs

- Reduce the risk to lives and property by improving system reliability.
- Reduce flood damages related to insufficient system capacity.
- Reduce seepage and related damages on lands adjacent to the levee system.
- Improve systemwide coordination of floodplain management activities among local, state, and federal entities.
- Reduce damages for the entire system by improving use of the existing designated reservoir flood space.
- Improve other beneficial uses related to flood-damage reduction.
- Improve system reliability by streamlining the permitting processes for flood-damage reduction, levee stabilization, and system maintenance activities.

Protect and Restore Riparian, Riverine, and Wetlands Habitats Systemwide

- Increase and improve riparian, floodplain, floodbasin, and riverine habitats throughout the San Joaquin River flood management system using an ecosystem approach.
- Promote the stability of native species populations and recovery of threatened and endangered species in the flood management system.
- Promote natural, dynamic, hydrologic and geomorphic processes in the flood management system.
- Reduce the impacts of past and current floodplain land use activities on hydrologic, geomorphic, and biological attributes of the river system.
- Improve operations of existing reservoirs and/or reserve water storage space in any new onstream and offstream reservoirs to benefit fishery and riparian habitats.

- Preserve agricultural productivity while promoting the ecological value of agricultural land.

- Incorporate environmental restoration features into the design of federal, state, and local elements of the San Joaquin River flood management system.

Resolve Policy Issues and Remove Institutional Barriers

- Develop evaluation criteria and a funding process that maximizes partnering potentials to implement needed system features.

- Implement improved floodplain management policies consistent with recommendations made by the FEAT report on floodplain management.

- Improve flood-damage-reduction management and environmental permitting procedures to minimize and resolve conflicts.

Appendix B. CALFED Conceptual Ecosystem Model and Attributes for Alluvial Rivers

CALFED has developed a framework for ecosystem models and ecosystem attributes in the Central Valley, including specific frameworks for lowland river-floodplain (alluvial river) ecosystems and Delta ecosystems. A diagram of the conceptual model for lowland river-floodplain systems is shown in Figure B-1. Upland habitat will be included in the EFM primarily to define the boundaries of riparian habitats. It will appear on maps in areas that are too removed from the river and the water table to support riparian or wetland habitats. Also, some riparian wildlife may have a strong preference for the edge between riparian and upland habitats. With respect to instream habitat, the EFM will focus on habitat attributes related to flooding and the winter flow regime. The following is a summary of attributes identified by CALFED scientists for these alluvial river ecosystems.

Hydrologic Attributes

General

- Minimum flow
  --for species viability
  --to maintain groundwater adequate for riparian vegetation

- Seasonal stage regime
  --for flushing flows
  --for groundwater recharge
  --for river-floodplain nutrient/etc. exchange

- Seasonal velocity regime
  --to be compatible with life stages
  --to maintain dynamic sediment transport

- Periodic flooding
  --for succession
  --diversity
  --river-floodplain exchanges

Lowland River-Floodplain Ecosystems

- flow persistence
- seasonal stage regime
- flooding regime
- hydrodynamic complexity
- groundwater exchange to support shaded riverine aquatic habitat
- flood attenuation (storage and release)

Geomorphic Attributes

General

- topography: alteration can fragment habitats
- channel dynamics: can inhibit movement of water, sediment, animals (unclear)
- substrate composition

Lowland River-Floodplain Ecosystems

- channel continuity
- channel-migration/floodplain-construction
- floodplain "backwater" features (side channels, oxbows, etc.)
- connection of river to floodplain and/or floodbasins
- sediment budget balance
- channel dynamics and substrate changes
- riparian zone width
- seasonal turbidity regime (fish migration cues)

Natural-Habitat Attributes

General

- "within-habitat" attributes, internal to a habitat
- "among-habitat" attributes

--disconnected habitats

prevent full community development,
limit viability and restrict distribution of habitats

Lowland River-Floodplain Ecosystems

- Among habitats
  --scope of natural-landscape mosaic
  --water and sediment quality

- Within habitats
  --Riverine habitats
    temperature, turbidity, nutrient concentration, substrate size consistent with location on gradient
    instream woody material
    natural levees (some benefit?)
    variable benthic topography (variable depth, flow, photics)
    dynamic islets and point bars
    sloughs, oxbows, and side channels
  --Riparian Forest
    natural vegetation communities arranged by terrace (low terrace: annual flood; higher terrace: 2- to 5-year flood)
    layering structure, density, width
  -Wetlands
    emergent density
    drainage-channel complexity
    velocity regime (slow)
    macrophyte and duckweed presence

Native Biological Community Attributes

General

- fundamental processes: primary production, nutrient cycling, exchange
- overall diversity
- fundamental aspects of community structure

Lowland River-Floodplain Ecosystems

- Riverine
  --downstream gradient from benthic algae to phytoplankton
  --native invertebrates and fishes
- Riparian
  --native assemblage of trees, shrubs, vines, grasses, according to terrace position or elevation

--diversity of insects, birds, herps, mammals (should be relatively high)

- Wetland
  --tules and wet prairies
  --bird diversity, especially wintering waterfowl

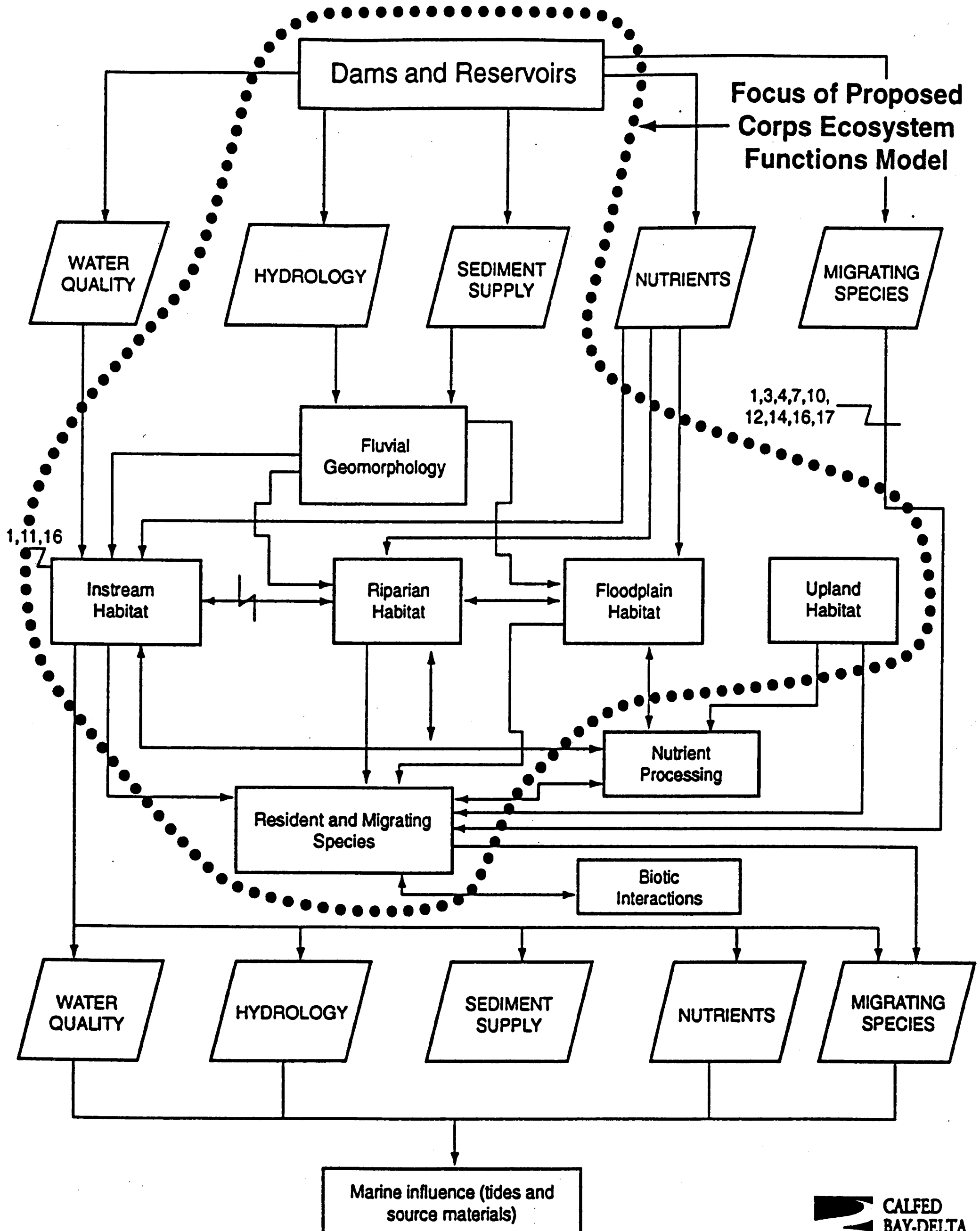
Community Energetics/Nutrient-Cycling Attributes

General

- energy flow and nutrient flow
- both abiologic (e.g., water circulation) and biologic (trophic dynamics) attributes

Lowland River-Floodplain Ecosystems

- seasonal nutrient influx from riparian zone (relatively large)
- primary productivity (relatively large)
- detritus export to San Francisco Bay (large)



Note:
The delineation of the "Focus of Proposed Corps Ecosystem Function Model" is shown to generally identify that portion of CALFED's Concept Model related to the Corps' efforts under the Comprehensive Study. The Corps recognizes that some important factors have not been included in this conceptual model formulated by CALFED (e.g., hydrology and sediment supply are affected by several factors in addition to dams and reservoirs).

Jones & Stokes Associates, Inc.

Figure B-1
CALFED Concept Model for Lowland River-Floodplain Systems

Appendix C. Model Limitations

The EFM will be a planning tool for describing existing and future no-project conditions, identifying environmental restoration opportunities, and evaluating a wide range of flood damage reduction and ecosystem restoration measures and combinations of measures. The EFM will focus on attributes considered essential for understanding the ecosystem as it relates to measures that will be considered in the study. The modeling effort will concentrate on those attributes that are feasible to model and measure within the time and budget of this study. Information about some aspects of ecosystem dynamics is scarce and will be addressed in the EFM to the extent possible given this limitation. Also, the resolution at which the model simulates spatial and temporal aspects of ecosystem function is limited. The model will quantify the amount of habitat potentially and actually available for selected species and communities along fairly long river reaches, floodbasins, and bypasses.

This appendix describes some of the recognized limitations of the initial EFM:

- **Selection of important ecosystem attributes is based on experienced professional judgement.** Selection of key attributes and appropriate indicators for them is based on the subjective judgement of ecologists experienced in the Sacramento and San Joaquin ecosystems. Attributes were selected that are likely to respond to implementation of the types of management measures under consideration in the Comprehensive Study (Table 1).

- **Known ecosystem attributes and relationships are not included in the model.** Structural attributes that are not simulated include the occurrence and populations of particular species and communities. Functional attributes that are not considered in the model include fire, local rainfall patterns, evapotranspiration, soil moisture balance, certain types of human disturbance (i.e., introduced species, hunting, and fishing), pollution, and specific interactions among species (i.e., competition, predation, and disease).

- **Selected biological attributes are limited to indicator species and major communities types.** By using indicator aquatic species and primary terrestrial habitat types and renewal processes, the model will include attributes important to most species that may be affected by management measures. Clearly, however, not all species needs are reflected in the model. The model allows for future incorporation of additional species or vegetation communities.

- **Spatial and temporal resolution will be limited.** The spatial resolution of geographic information in the EFM will range from tens to hundreds of feet for topographic, soil type, and land use maps to thousands of feet between cross sections in the hydraulics models. The shortest time scale of timeseries data that will be used in the model is 1 day (except that peak rather than maximum daily flows may be used in the flood hydraulics models). Continuous variability in flow and in other environmental conditions, such as evapotranspiration and water temperature, will not be considered in the model. Ecosystem dynamics, such as channel migration and plant succession, will not be assigned to specific locations at specific times in the initial version of the EFM, but will be represented as overall average annual rates for the simulated reach.

- **Water temperature will not be explicitly simulated.** Water temperature exerts a strong influence on the reproduction, growth, migration, and survival of all aquatic organisms. Floodplains, bypasses, and floodbasins greatly increase the range and spatial variability of temperatures accessible to fish. Temperature in areas of shallow inundation can be 10-15°C higher than in the main channel. Simulation of water temperature throughout the flow system would require a substantial effort and will not be included in the initial EFM. Instead, the model will implicitly assume that measures that increase the area, frequency, and duration of shallow inundation will automatically increase the range of water temperatures present along the simulated reach.

- **Past hydrology will be used to predict future hydrology.** Daily, seasonal, and annual streamflow variability will be calculated from historical streamgage records. These records do not accommodate climate change.

- **Nonlinear feedback effects will not be directly simulated.** The modeling approach implicitly assumes that channel and floodplain geometry remain relatively constant over the long term, even though the model includes processes, such as bed aggradation/degradation and meandering, that can alter channel geometry. Also, the EFM will assume that physical conditions affect biological conditions, but not vice versa. On completion of H&H models, however, effects on hydraulic roughness of inchannel vegetation and consequent effects on flood stage and inundated area can be simulated in the H&H model and used in the EFM. Similarly, floodplain vegetation affects flow velocity and sediment deposition in overbank areas and consequently affects floodplain accretion and inundation frequency and duration. These interactions will not be included explicitly in the EFM because they normally are of secondary importance, but they can be investigated for a particular measure and location if concern for their importance arises.

- **Shallow-groundwater data are scarce.** Depth to the water table is an important factor affecting the distribution of riparian vegetation. Data for this variable are limited because few shallow monitoring wells are present along the major river channels. Water supply wells indicate the water levels in deep aquifers used for water supply, and water levels in those aquifers are frequently much lower than in surficial strata near rivers. Where data are absent, the model will assume that the water table projects horizontally from the river channel at the same level as the low-flow water surface in the channel during the growing season. Along many reaches, this assumption is probably reasonable at distances of up to several hundred feet from the channel along perennial flow reaches. For larger distances, groundwater boreholes will be needed to assess the potential for riparian restoration.

Appendix D. EFM Modeling Tasks

STEP 1. HYDRAULIC MODELING

1-1. Develop Digital Terrain Information

Inchannel and floodplain topography

1-2. Assemble Stream Gage Records

1-3. Floodflow Analysis

A. Divide Flow System into Segments

Use high-flow channel alignments
Place segment boundaries at all concentration or flow split points
Additional boundaries every 1,000-5,000 feet along channels

B. Tabulate Cross-Section Geometry at Each Segment

C. Calculate Floodflows for Each Segment

Use combination of HEC-1, HEC-5, and historical flood frequency plots
Mass continuity between reaches is essential
Select range of floodflows for simulation (durations and frequencies from 100-year peak to 25-year, 7-day maximum flow)

D. Calibrate Roughness Coefficients

Obtain measured flood profiles from historical floods
Obtain gaged historical flows for those floods
Calibrate roughness so that simulated profile matches historical profile

E. Simulate Floodflow Profiles

Result: Water-surface elevation at each segment for selected high flow rates

1-4. Nonfloodflow Analysis

A. Adjust Network and Channel Geometry

Adjust segment lengths to account for low-flow channel sinuosity

B. Select Gage Records for Low-Moderate Flow Analysis

Shorter records (10-20 years) acceptable for low-moderate flow characterization
Mass continuity between reaches is not essential
Select representative historical period for daily flow-duration and timeseries analysis
Create complete set of daily flows for each reach for the historical period, synthesizing flows by correlation if necessary

C. Calibrate Low-Moderate Flow Roughness Coefficients

Find aerial photographs taken when flow approximately equals bank full discharge
Find flow on date photographs were taken
Use geographic information systems (GIS) and digital terrain model to map floodplain at low flow
Adjust roughness coefficients until simulated floodplain matches air photo
Double check with measured water-surface elevations, where available

D. Simulate Low-Moderate Flows

For each reach, select approximately five low flows for simulation, ranging from the minimum daily flow of record to the 10-year, 1-day high flow
Simulate water-surface elevation at each cross section at each flow using the low-flow segment lengths and roughness coefficients

1-5. Hydraulic Geometry Tabulation

A. Develop Depth-Discharge Rating Curves

Combine data for floodflows and low flows
Extract mean channel flow depth from HEC-RAS or UNET output for each flow
Fit with polynomial or power function
Unique curve for each river segment

B. Develop Velocity-Discharge Rating Curves

Combine data for floodflows and low flows
Extract mean channel velocity from HEC-RAS or UNET output for each flow
Fit with polynomial or power function
Unique curve for each river segment

STEP 2. TIMESERIES AND GEOMORPHOLOGY ANALYSIS

2-1. Sediment Transport Analysis

A. Tabulate Inchannel Grain Size Distribution

Obtain existing sieve analyses of bed material in simulated reach
Pick grain sizes of biological relevance as boundaries for size class intervals
Tabulate average percent by weight in each class interval

B. Calculate Mean Channel Velocity Regime

Document velocity regime associated with the grain size distribution by using hydraulics models to tabulate mean channel velocity for selected flow magnitudes
Create flow-duration curve for the simulated reach from daily flow record (log-log plot of flow versus percent of time exceeded)
Convert flow duration curve into a mean channel velocity-duration curve using the velocity-discharge rating curve

2-2. Channel Migration Analysis

A. Develop Functional Relationships for Meandering

Use maps and air photos to tabulate historical channel migration rates (percent relocation of low-flow channel) for each reach
Match migration events with estimated flow to develop function relating flood magnitude and percent channel relocation
Refine flow-migration relationships through sensitivity analysis of a meander model.
Also simulate effects of bank protection and channel reconfiguration on meander rate.

B. Calculate Reference Meandering Condition

Calculate long-term average annual percent channel migration under reference condition flows using flood-probability and flow-duration curves

2-3. Depth, Velocity, and Inundated Area Duration-Frequency Analysis

A. Select Habitat Criteria for Each Indicator Species and Community

Complete literature research regarding habitat criteria for species and communities simulated in the EFM

Tabulate physical habitat criteria for species and communities

Convert depth and velocity criteria to discharge criteria using depth-discharge and velocity-discharge rating curves

For each species and community type, specify minimum and/or maximum values for the following criteria to screen historical record of daily flows:

Season (beginning and ending Julian day)
Duration ("n" days)
Frequency (condition must be met in "x" years out of every "y" years)

B. Process Daily Flow Records for Each Reach

Pick the seasonal window of analysis

Use an n-day moving window to find minimum or maximum flow that meets the duration criterion in the selected season of each year

Process annual timeseries to find minimum or maximum flow that meets the frequency criterion

STEP 3. MAPPING ANALYSIS

3-1. Create Attribute and Land Use Maps

A. Inundation Maps

Enter simulated water-surface elevations as point data at hydraulics model x-section locations. [Note: until hydraulics models are completed, use normal-depth elevations.]

Interpolate water-surface profile linearly between points

Superimpose water-surface profile on channel and floodplain topography to map inundated area

Repeat for selected flow levels between low flows and floodflows that meet inundation depth, or velocity season-duration-frequency criteria

B. Soil Suitability Map

Obtain soil survey reports for all floodplain areas

Create GIS soils map along rivers

Combine soil types into two texture categories (coarse and fine, suitable for riparian and wetland, respectively)

C. Depth-to-Groundwater Map

Obtain available groundwater elevation data from existing shallow boreholes [Note: in the absence of measured data, assume water table elevation equals river surface elevation or contoured water levels from water supply wells.]
Obtain maps of regional groundwater levels in water supply aquifers for inferences about leakage to or from shallow strata near the rivers.

D. Land Use Map

Create digital map of land use categories that affect biological ecosystem attributes (floodplain soil texture, channel substrate texture, inundation, depth to groundwater, and possibly water depth and velocity)
Create habitat effect matrix of land use vs. biological attributes

3-2. Create Habitat Maps and Tables

A. Potential Habitat

Use GIS to overlay maps of habitat criteria for each biological attribute category (soil texture, channel substrate texture, inundation, depth to groundwater, and possibly depth and velocity)
Generate polygons where criteria are all suitable
Calculate and statistically summarize total habitat area and patch characteristics using FRAGSTATS (GIS software for calculating polygon sizes, shapes, and mosaic patterns)

B. Actual Habitat

Use GIS to overlay land use map on potential habitat map
Modify potential habitat areas where land use is incompatible with or alters habitat (note that agriculture can be beneficial or detrimental, depending on the species)
Calculate and statistically summarize total habitat area and patch characteristics using FRAGSTATS

3-3. Adjust for Nonlinear Variables

Compare actual habitat map with future no-project conditions
If actual habitat would result in substantial long-term change in vegetation density or erosion/deposition, adjust hydraulic roughness and topography accordingly and resimulate

STEP 4. REPEAT ANALYSIS FOR MANAGEMENT MEASURES

4-1. Update Input Parameters and Resimulate

Flow regime affected by reservoir capacity, reservoir operation, restored overflow basins, and expanded floodplains
Depth-discharge relationship and inundated area affected by vegetative roughness (i.e., restoration or clearing of channel and floodplain vegetation)
Inundated depth and area affected by topography (e.g., levee location and channel configuration)
Meander rate affected by bank protection or change in flow regime
Actual habitat affected by land use

4-2. Compare Results with Reference Conditions

Reference conditions include existing, future no-project, and natural conditions
Compare total areas of habitat for each species/guild/community
Compare patch characteristics of each habitat type
Compare velocity regimes and infer tendency toward deposition or erosion
Compare meander rates and proportional area of vegetation succession stages